NEW

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# BLACK HOLES

## UNCOVER THE TRUTH ABOUT THE DEATH OF STARS

**50 FACTS** ABOUT BLACK HOLES

**WHAT'S LIFE LIKE** AROUND BLACK HOLES?

THE HUNT FOR BLACK AND WHITE HOLES

FROM THE MAKERS OF SPACE.com

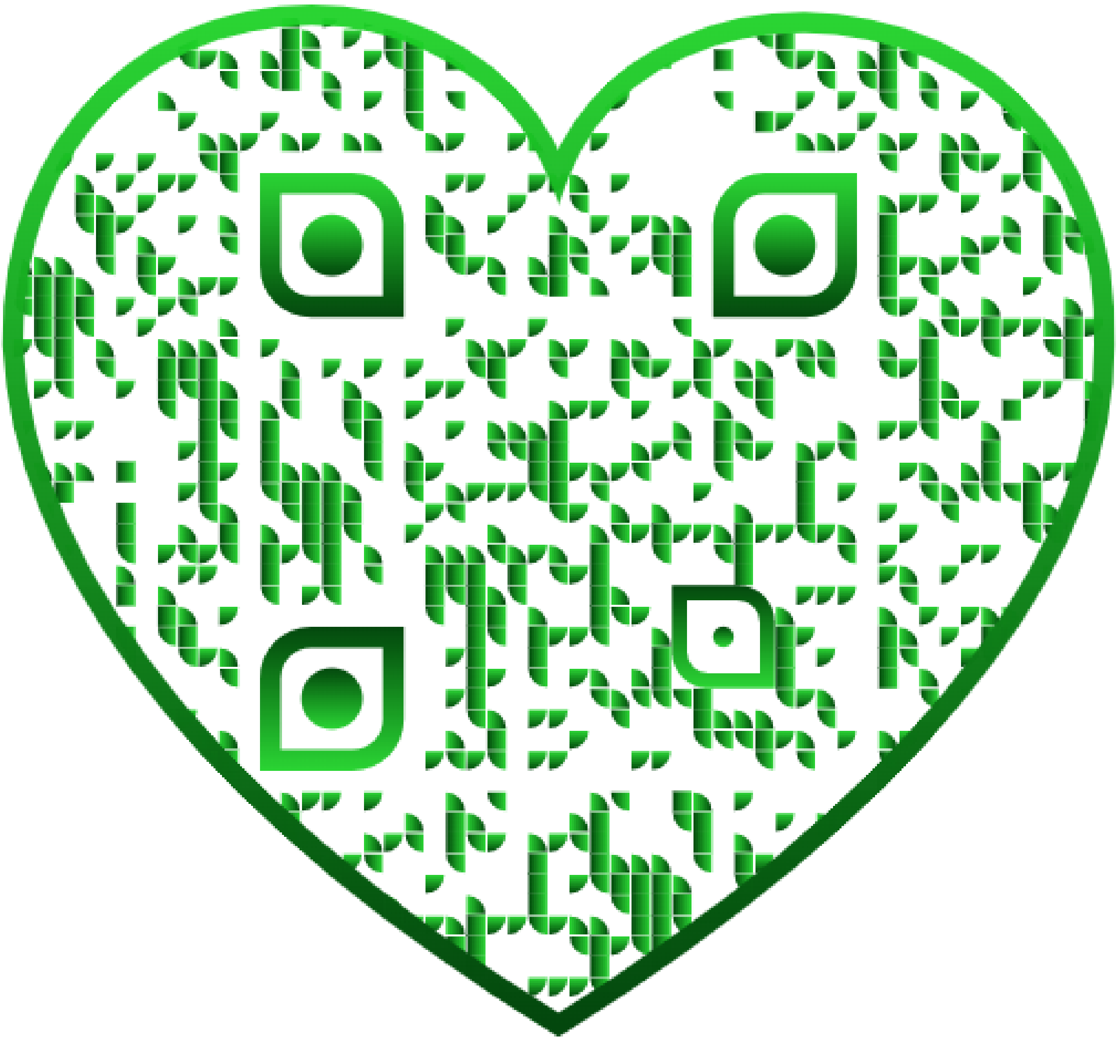
Digital Edition

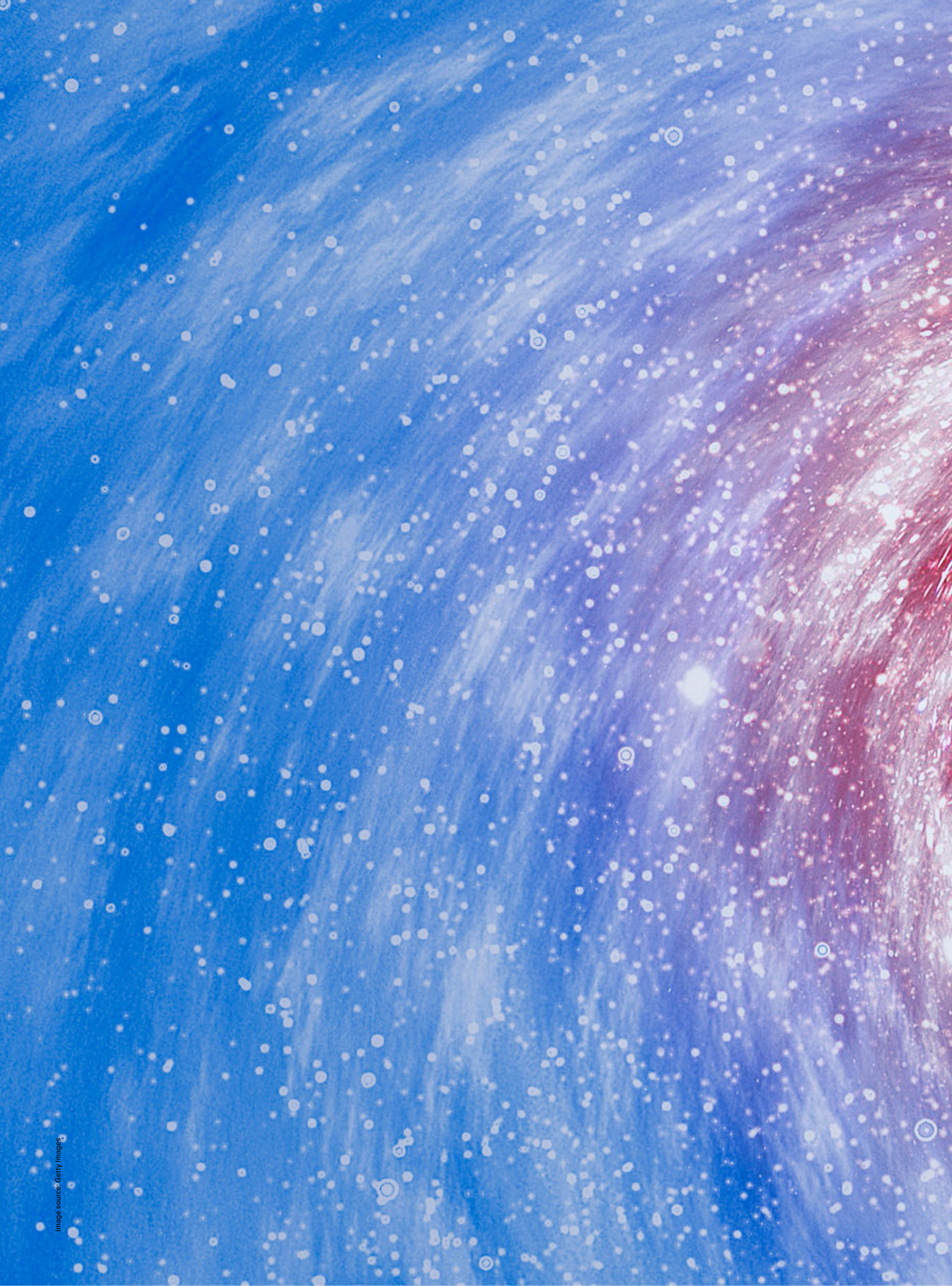
FIFTH EDITION

WHAT MAKES A BLACK HOLE

## SUPERMASSIVE

INSIDE A BLACK HOLE • HAVE PARALLEL WORLDS FIGURED THEM OUT? • HOW BLACK HOLES WORK





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# Welcome

We may not be able to see them, but black holes are out there. There's even one at the centre of the Milky Way. But what is a black hole? And how are they made?

These questions and more are answered in this new title from the makers of All About Space. Uncover the truth behind the creation of black holes, and get up close with the primordial giants that have been around since just after the Big Bang. Find out what happens when black holes turn white, and take a trip to the Event Horizon Telescope to see how the first-ever picture of a black hole was taken.

We also take a look at questions that have plagued astrophysicists for decades. Can life actually exist around black holes? Can a spaceship be powered by a black hole's energy? And could these cosmic enigmas even be gateways to parallel universes?

FUTURE

# BLACK HOLES

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Senior Designer **Adam Markiewicz**
Compiled by **April Madden & Phil Martin**
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Editorial Director **Jon White**
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**All About Space Editorial**
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Commercial Director **Clare Dove**

**International**
Head of Print Licensing **Rachel Shaw**
licensing@futurenet.com
www.futurecontenthub.com

**Circulation**
Head of Newstrade **Tim Mathers**

**Production**
Head of Production **Mark Constance**
Production Project Manager **Matthew Eglinton**
Advertising Production Manager **Joanne Crosby**
Digital Editions Controller **Jason Hudson**
Production Managers **Keely Miller, Nola Cokely,**
**Vivienne Calvert, Fran Twentyman**

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For enquiries, please email: mfcommunications@futurenet.com

**GPSR EU RP (for authorities only)**
eucomply OÜ Pärnu mnt 139b-14 11317, Tallinn, Estonia
hello@eucompliancepartner.com, +3375690241

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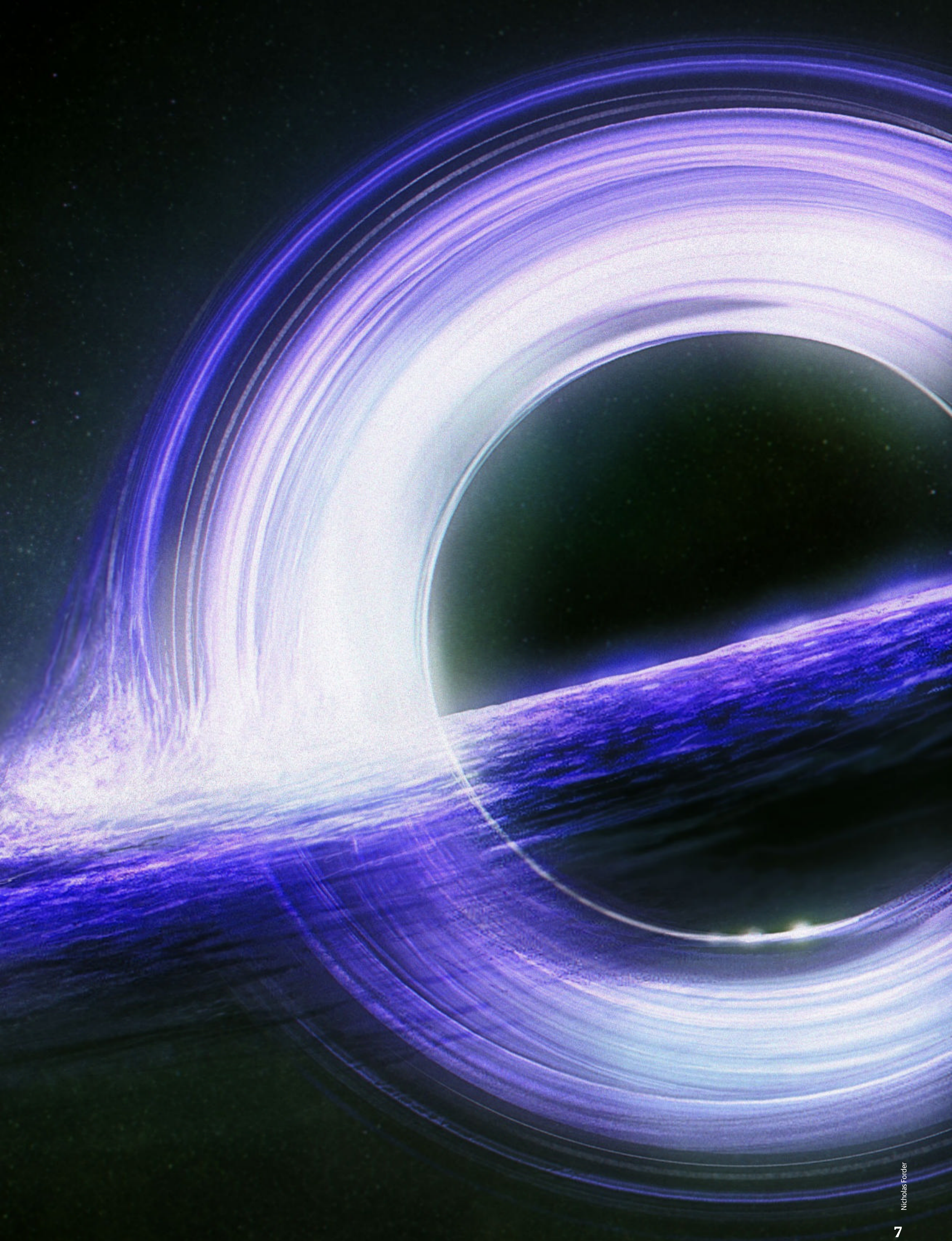

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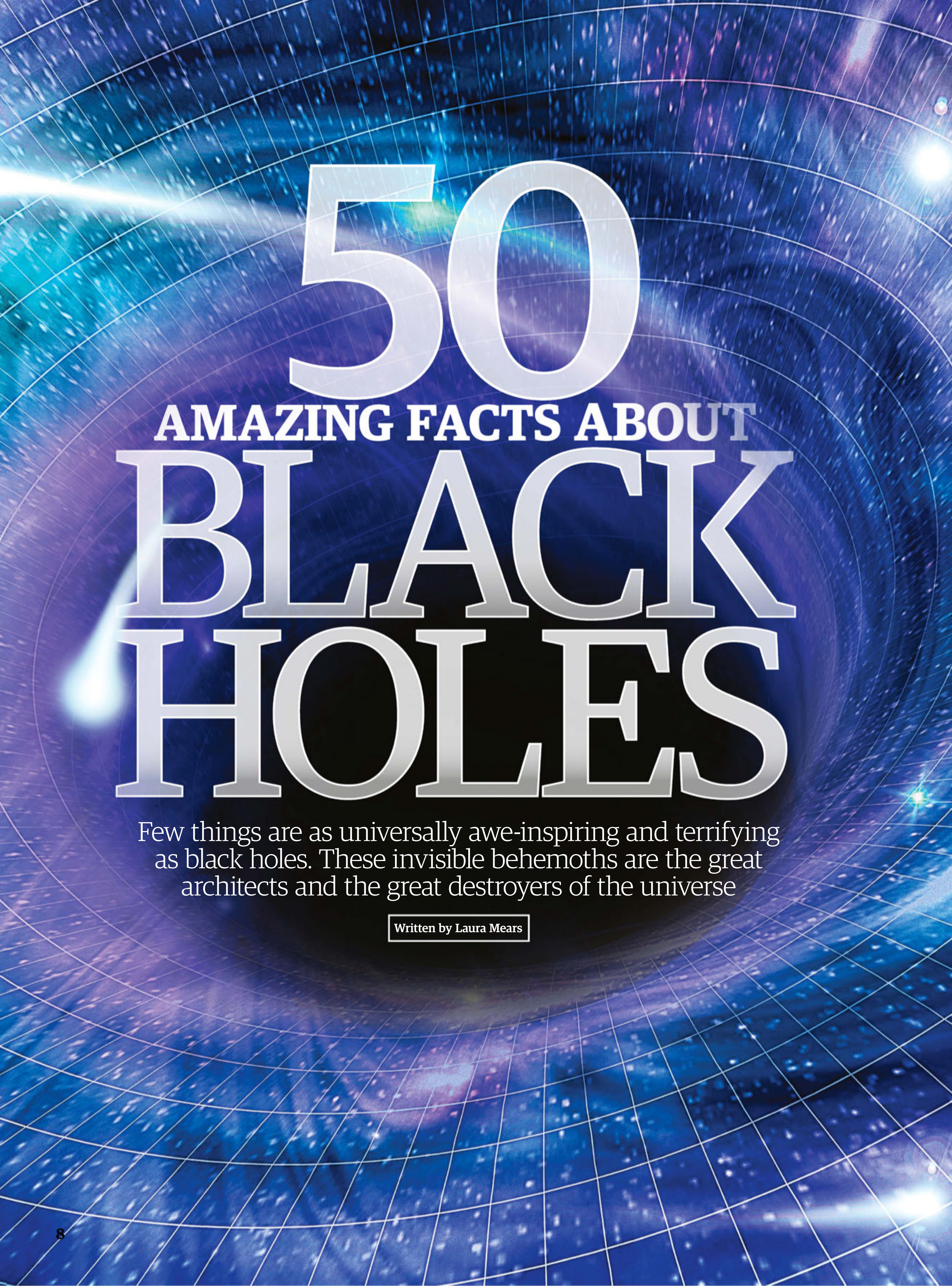


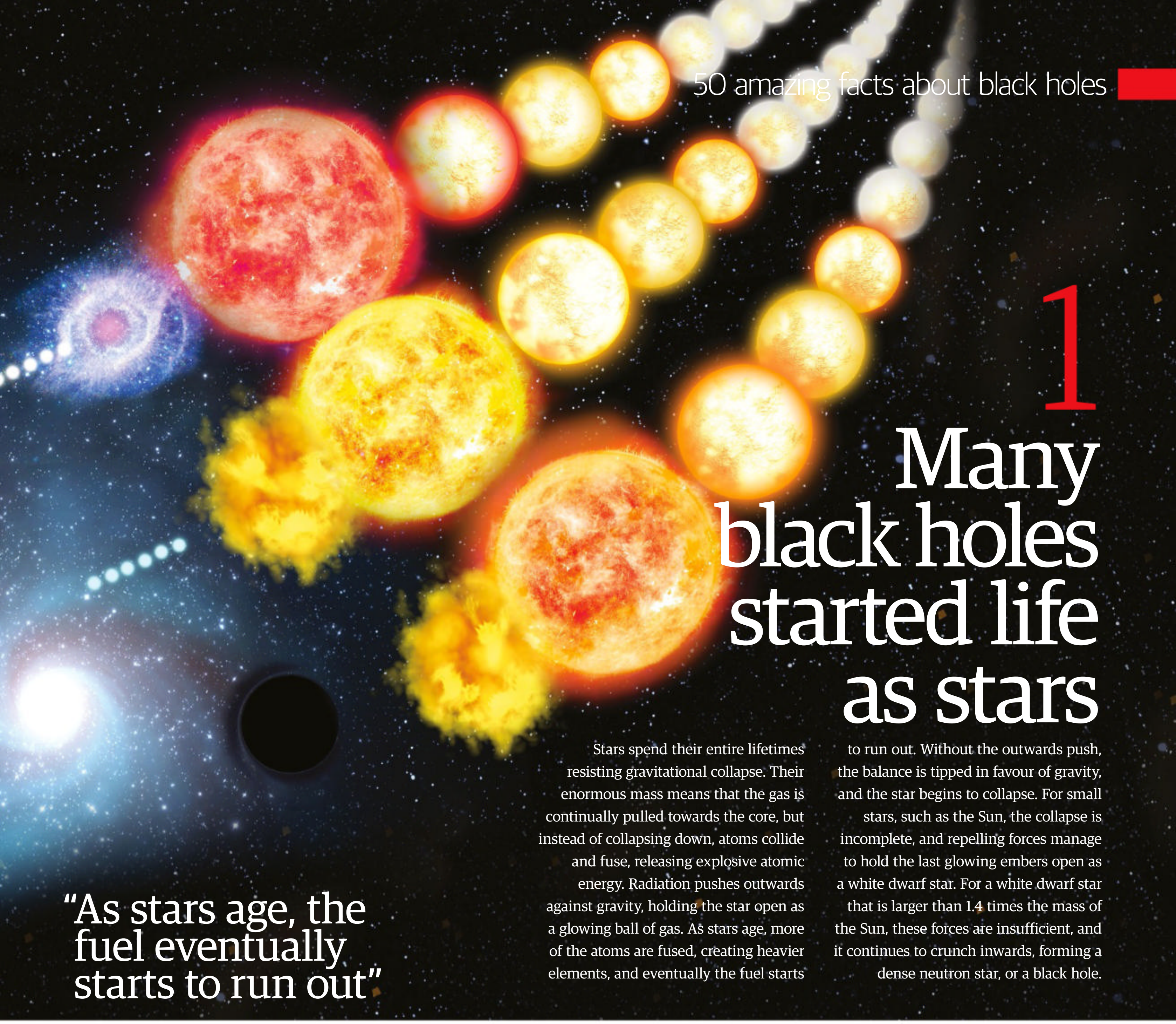
# 50

## AMAZING FACTS ABOUT

# BLACK HOLES

Few things are as universally awe-inspiring and terrifying as black holes. These invisible behemoths are the great architects and the great destroyers of the universe

Written by Laura Mears



# 1

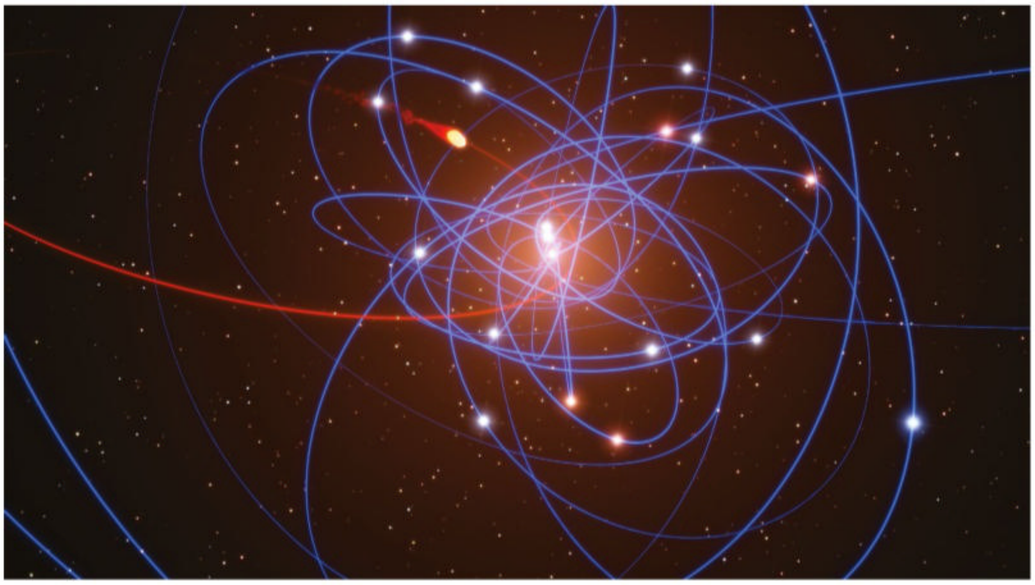
# Many black holes started life as stars

Stars spend their entire lifetimes resisting gravitational collapse. Their enormous mass means that the gas is continually pulled towards the core, but instead of collapsing down, atoms collide and fuse, releasing explosive atomic energy. Radiation pushes outwards against gravity, holding the star open as a glowing ball of gas. As stars age, more of the atoms are fused, creating heavier elements, and eventually the fuel starts to run out. Without the outwards push, the balance is tipped in favour of gravity, and the star begins to collapse. For small stars, such as the Sun, the collapse is incomplete, and repelling forces manage to hold the last glowing embers open as a white dwarf star. For a white dwarf star that is larger than 1.4 times the mass of the Sun, these forces are insufficient, and it continues to crunch inwards, forming a dense neutron star, or a black hole.

> "As stars age, the fuel eventually starts to run out"

## 2 Supermassive black holes do not destroy everything around them

Actively feeding supermassive black holes are some of the most violent places in the universe, and quasars devour the equivalent of tens to thousands of Suns each year, but amazingly, the galaxies that surround them do not disappear into the abyss. Despite their frightening reputation, black holes do not actually behave very differently to other massive objects in the universe, unless you get too close. Just as the Earth will not spontaneously crash into the Sun, objects in stable orbits around black holes are in no danger of being swallowed.



## 3 Black holes slow the flow of time

To an outside observer, an object falling into a black hole appears to slow down, before stopping, caught in suspended animation at the boundary.

## 4 A black hole reveals no clues about what it has swallowed

As matter enters a black hole, it is stretched, pulled and eventually shredded. Even if something were to leak out, it would bear no resemblance to what went in.

## 5 They have no size limit

In theory, black holes continue to grow in size indefinitely, but just how large they are able to get depends on their local environment.

## 6 Supermassive black holes are around the same mass as the solar system

Supermassive black holes contain the mass of at least 100,000 Suns compressed into a space that is around the size of our solar system.

## 7 It's the size of a black hole that matters, not its mass

Just a few micrograms of matter would be enough to create a black hole if it was compressed into a small enough space.

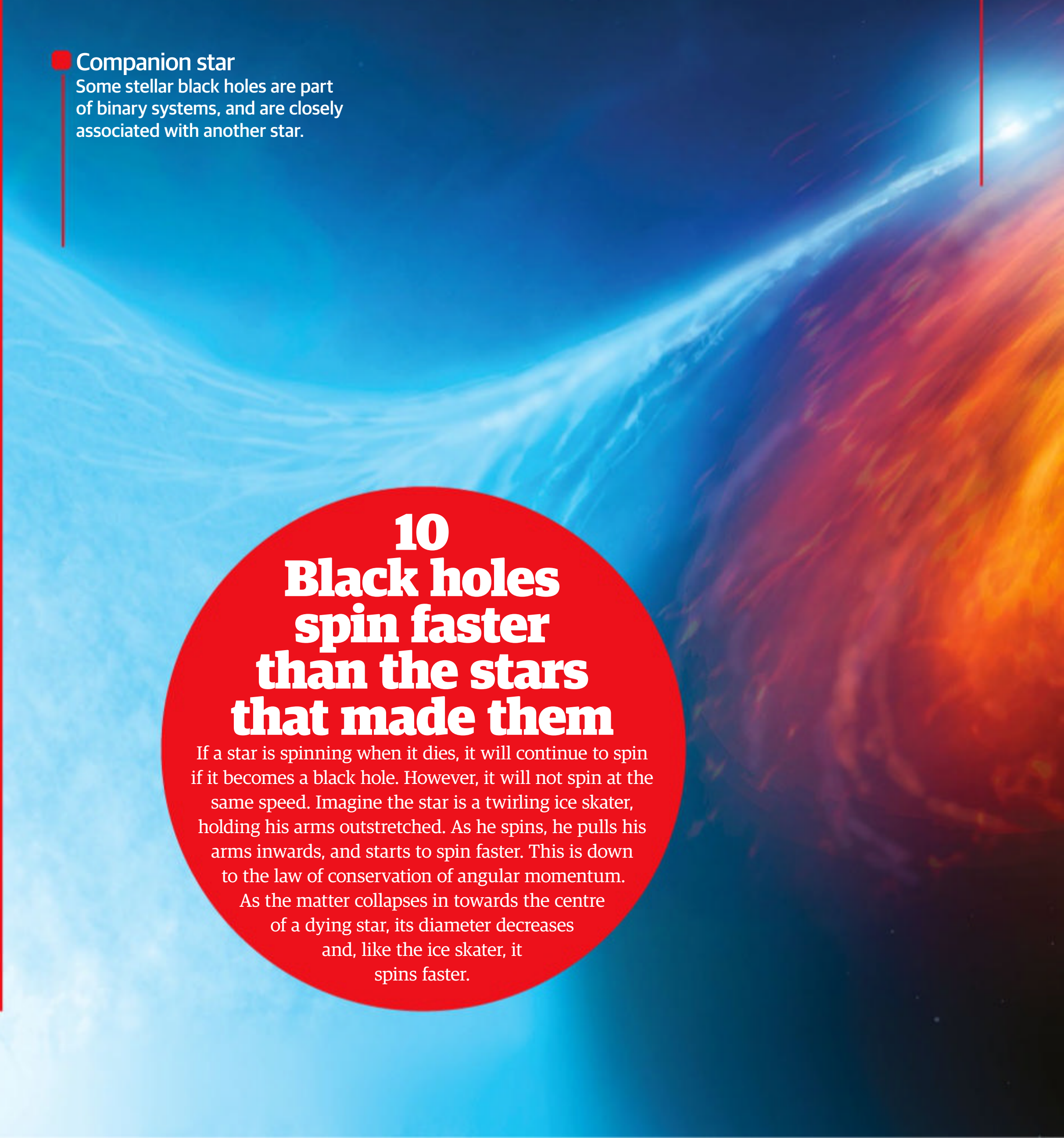
## 8 Some galaxies might harbour ultramassive black holes

The galaxy OJ 287 has two black holes, one of which is thought to contain the mass of around 18 billion Suns.

# 9 Black holes feed on stars, revealing their location

Black holes cannot be seen directly, but the effect they have on their surroundings often reveals their presence. In the Cygnus constellation, a blue supergiant star is being pulled into a teardrop shape, causing its light to flicker as it spins. The star orbits once every 5.6 days, and as it turns, the outer layer of gas is stripped away from its surface at 1,500 kilometres (932 miles) per second as it is funnelled towards an invisible point.

The supergiant is part of a binary system, and is locked in a fatal dance with a black hole, known as Cygnus X-1. As the black hole spins, space and time spiral up with it, and dust and gas from the star accumulate in a vast swirling whirlpool known as the accretion disc. Particles spiral towards the event horizon, like water circling a drain, and as they tumble inwards the friction releases bright flashes and flares of X-ray light.

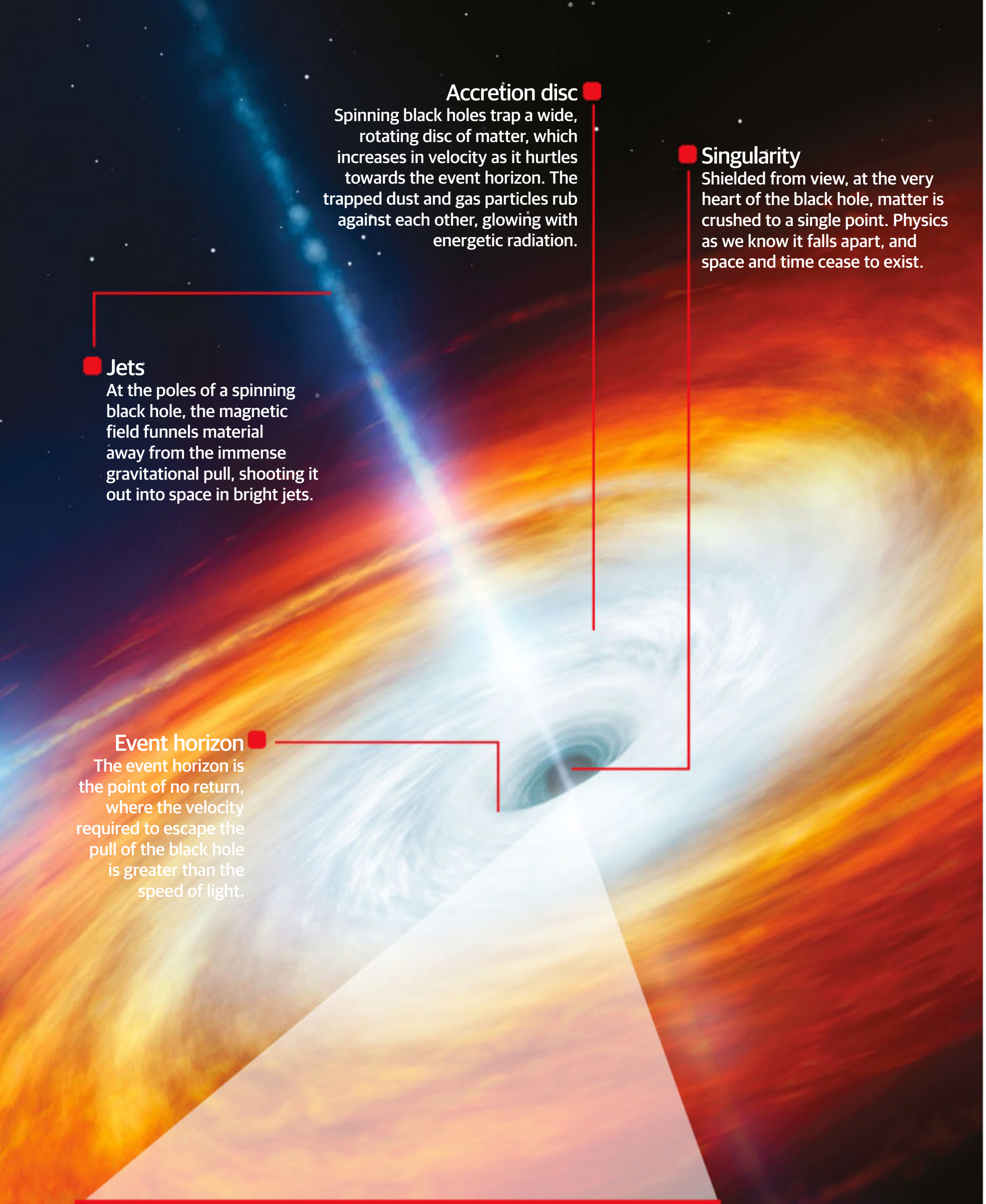


**Magnetic field lines**
As black holes spin, the magnetic fields within their accretion discs will spiral up and down, and they create a doughnut-shaped field around the disc.

**Companion star**
Some stellar black holes are part of binary systems, and are closely associated with another star.

## 10 Black holes spin faster than the stars that made them

If a star is spinning when it dies, it will continue to spin if it becomes a black hole. However, it will not spin at the same speed. Imagine the star is a twirling ice skater, holding his arms outstretched. As he spins, he pulls his arms inwards, and starts to spin faster. This is down to the law of conservation of angular momentum. As the matter collapses in towards the centre of a dying star, its diameter decreases and, like the ice skater, it spins faster.



**Accretion disc**
Spinning black holes trap a wide, rotating disc of matter, which increases in velocity as it hurtles towards the event horizon. The trapped dust and gas particles rub against each other, glowing with energetic radiation.

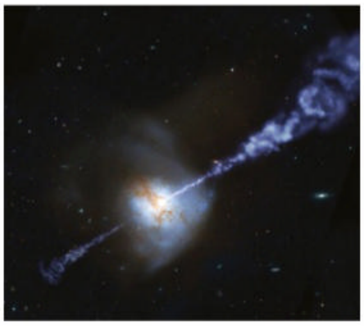
**Singularity**
Shielded from view, at the very heart of the black hole, matter is crushed to a single point. Physics as we know it falls apart, and space and time cease to exist.

**Jets**
At the poles of a spinning black hole, the magnetic field funnels material away from the immense gravitational pull, shooting it out into space in bright jets.

**Event horizon**
The event horizon is the point of no return, where the velocity required to escape the pull of the black hole is greater than the speed of light.

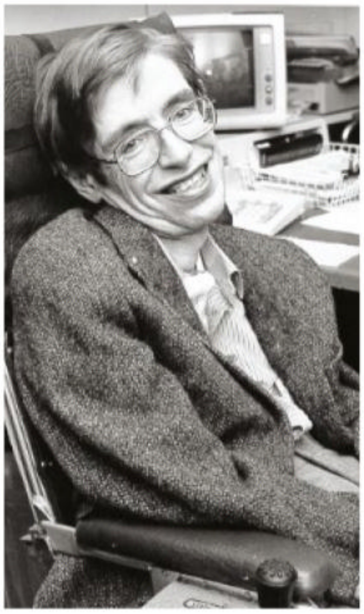
## 11 The centre of a black hole could contain a singularity

The event horizon of a black hole can measure thousands of kilometres in diameter, but once matter crosses over the edge it does not stop moving. Exactly what happens on the inside is debated, but according to Einstein's theory of general relativity, the curvature of space-time inside a black hole is extreme, and everything is directed towards a single point, known mathematically as a singularity. Every possible path leads back to the centre, and matter becomes so crushed, into such a tiny space, that it is unrecognisable. The singularity is infinitely small, and infinitely dense, creating an infinite curvature in space-time. Within a region of space known as the event horizon, anything that crosses over is compelled towards the centre with no hope of escape.



## 12 Some black holes have jets

Some black holes spew impressive amounts of energy from their poles, marking their location like a beacon. As dust and gas race towards the event horizon of a spinning black hole, magnetic field lines direct some of the energy outwards, funnelling it into two energetic jets, like a particle accelerator. NASA's Wide-field Infrared Survey Explorer (WISE) has identified a pair of black holes orbiting one another, which together create gravitational and magnetic disturbances so intense that their jets are being warped and twisted into ribbon-like spirals.



## 13 They slowly leak radiation

Stephen Hawking showed that black holes could actually radiate energy, known as Hawking radiation, releasing their scrambled contents back into the universe.

## 14 It takes millions of years to orbit our supermassive black hole

Sagittarius A* lies around 26,000 light years from the Solar System, and it takes 225 million years for us to complete a single orbit around the galactic centre.

## 15 They were originally known as dark stars

The idea of black holes has been around much longer than the science that predicts their existence, but in the 18th century they were known as 'dark stars'.

## 16 Cygnus X-1 was the first black hole to be identified

Cygnus X-1 is one of the brightest radio sources in the sky, and is currently in the process of devouring a blue supergiant.

## 17 Black holes create waves

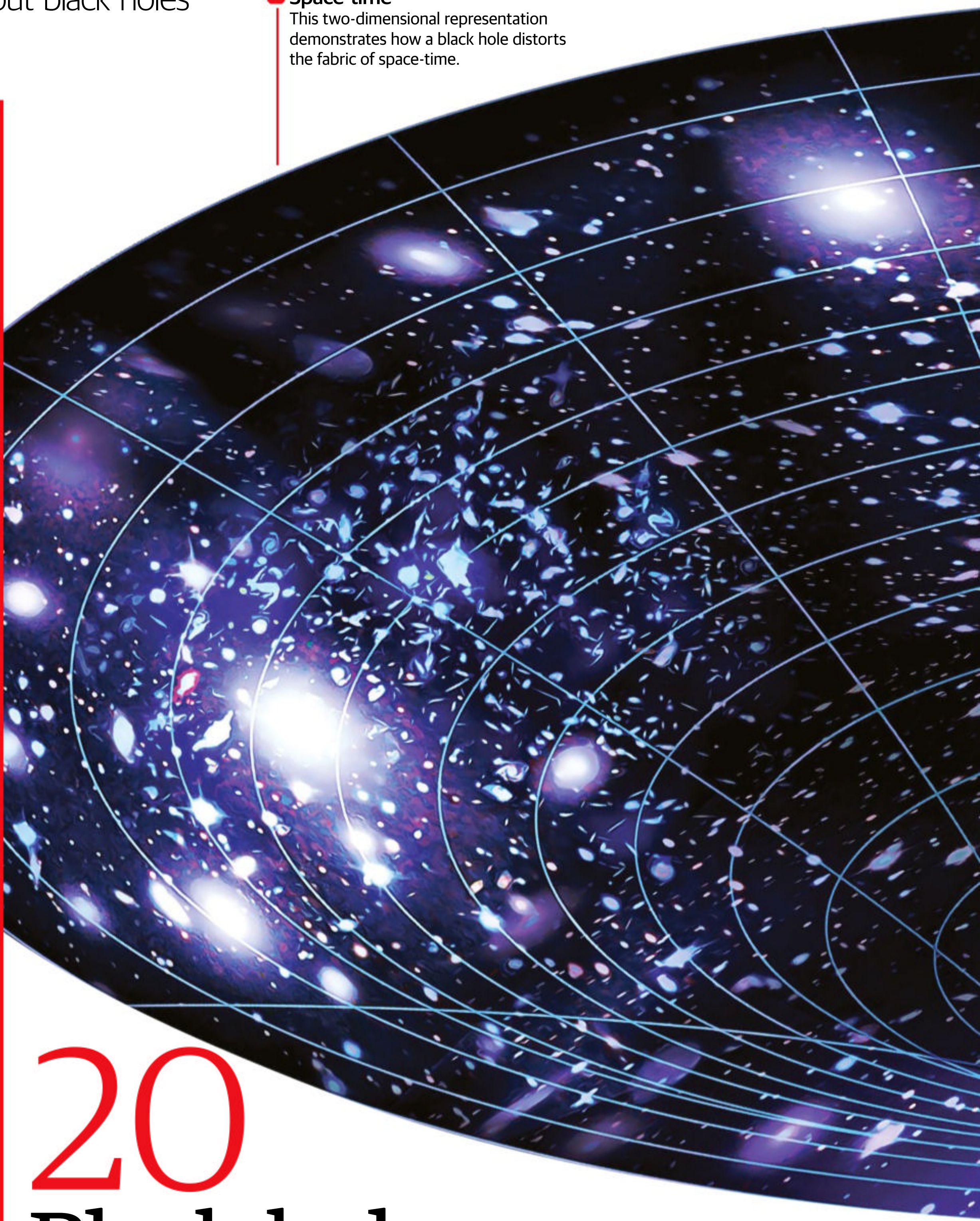
Albert Einstein predicted that as massive objects, like black holes, move through space, they create gravitational waves that ripple through space-time.

## 18 The universe is shaped by black holes

Supermassive black holes are found at the heart of almost all large galaxies, and act as the linchpins of the universe, around which stars and planets turn.

## 19 Stellar black holes contain the mass of five or more Suns

Black holes formed during the death of a star usually contain at least as much mass as five Sun-sized stars, compressed into an area measuring just a few kilometres across.

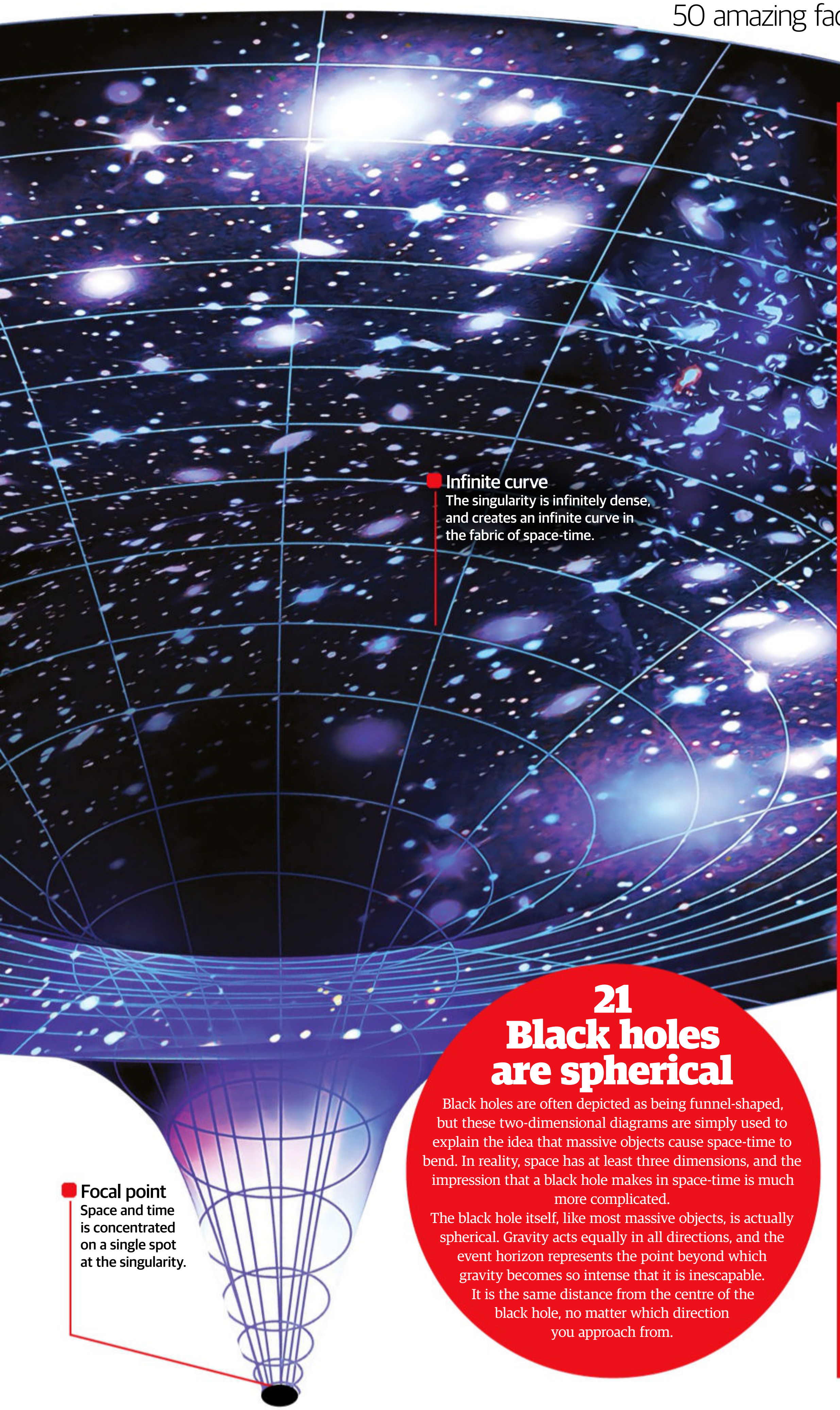


**Space-time**
This two-dimensional representation demonstrates how a black hole distorts the fabric of space-time.

## 20
## Black holes bend space-time

Albert Einstein showed that the universe is made from a fabric, known as space-time, and, just like a piece of cloth, it can be bent, twisted and stretched. Massive objects, including planets and stars, make dips in the fabric of space-time, like bowling balls sitting on top of a trampoline. The more mass that is collected in one area, the more of an impression it makes in the fabric, and the more energy is required to escape its gravitational field.

One object in orbit around another can be thought of as being similar to a cyclist in a velodrome. The cyclist is trying to travel in a straight line, but the curved floor forces them to move around in circles. If they pedal faster, they might be able to get up enough speed to climb out of the top of the dome, and if they slow down, they will start to drift back in towards the centre.



**Infinite curve**
The singularity is infinitely dense, and creates an infinite curve in the fabric of space-time.

**Focal point**
Space and time is concentrated on a single spot at the singularity.

## 21 Black holes are spherical

Black holes are often depicted as being funnel-shaped, but these two-dimensional diagrams are simply used to explain the idea that massive objects cause space-time to bend. In reality, space has at least three dimensions, and the impression that a black hole makes in space-time is much more complicated.

The black hole itself, like most massive objects, is actually spherical. Gravity acts equally in all directions, and the event horizon represents the point beyond which gravity becomes so intense that it is inescapable. It is the same distance from the centre of the black hole, no matter which direction you approach from.

## Interview

We spoke to head of the Nuker Team, Prof Douglas Richstone, about the origin of supermassive black holes

### 22 Almost every good-sized galaxy has a supermassive black hole

"For every galaxy that is reasonably good sized and regular (that is, a galaxy with a disc and a bulge, and possibly spiral arms, or a so-called elliptical galaxy that looks round) there is a black hole. Moreover, the black hole's mass tracks the mass of the host galaxy (and is about 1/1,000 of the galaxy's mass). These black holes range from 1 million to nearly 10 billion solar masses.

"However, for galaxies that are very small, or irregular, or possibly only have a disc and no round component (bulge), the situation is much more complicated. Some of these galaxies appear to have black holes and others don't."

### 23 Quiet supermassive black holes used to be quasars

"We don't know for certain how the big black holes noted above form, but there is a clue. The amount of mass in galaxies at present tied up in black holes is almost exactly the amount of mass needed to power quasars (very bright objects thought to be black holes accreting matter) when the universe was about a fifth of its present age. So it is reasonable to identify the black holes in galaxies now as the relics of quasars."

## 24 It is impossible to see them directly

Black holes do not emit or reflect electromagnetic radiation (except Hawking radiation), but their gravitational effects are detectable.

## 25 Some black holes spin at half the speed of light

By looking at the pattern of X-rays in the area surrounding a black hole, the speed at which it is spinning can be determined.

## 26 There are two types of black hole

Schwarzschild black holes are the simplest, and are made up of just an event horizon and a singularity. Kerr black holes rotate, and have a third component known as the ergosphere.

## 27 Black holes are noisy

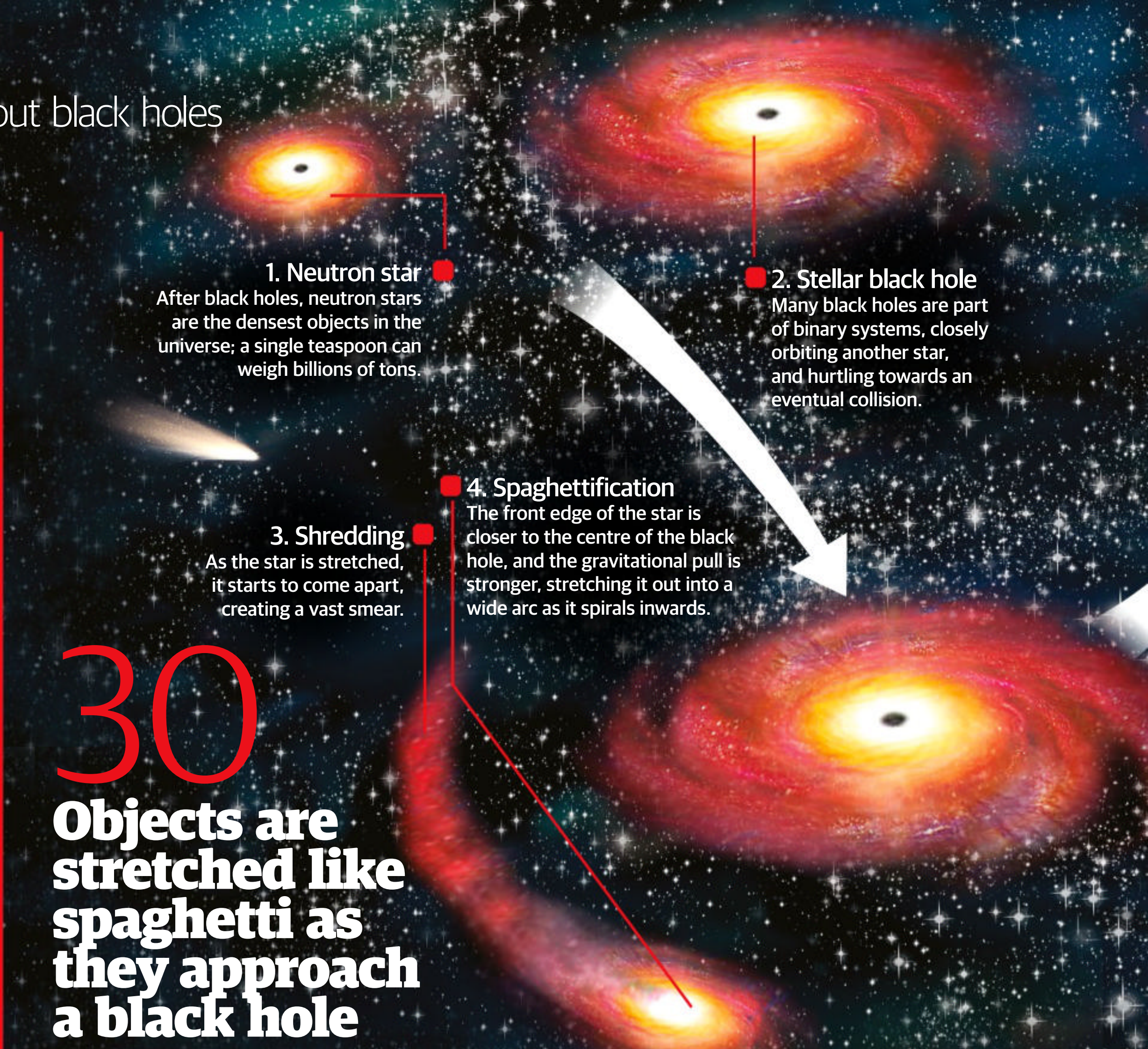
In 2003, NASA's Chandra X-ray observatory revealed that a black hole in the Perseus cluster makes a sound in the pitch of B flat.

## 28 We'll never know what is really inside a black hole

Light cannot escape across the event horizon of a black hole, preventing us from seeing in; there is no definitive answer about what really happens inside a black hole.

## 29 One day, black holes will dominate the universe

Black holes evaporate so slowly that they will exist long after the last of the stars fade and die, leading scientists to predict that one day they will be all that is left in the universe.



**1. Neutron star**
After black holes, neutron stars are the densest objects in the universe; a single teaspoon can weigh billions of tons.

**2. Stellar black hole**
Many black holes are part of binary systems, closely orbiting another star, and hurtling towards an eventual collision.

**3. Shredding**
As the star is stretched, it starts to come apart, creating a vast smear.

**4. Spaghettification**
The front edge of the star is closer to the centre of the black hole, and the gravitational pull is stronger, stretching it out into a wide arc as it spirals inwards.

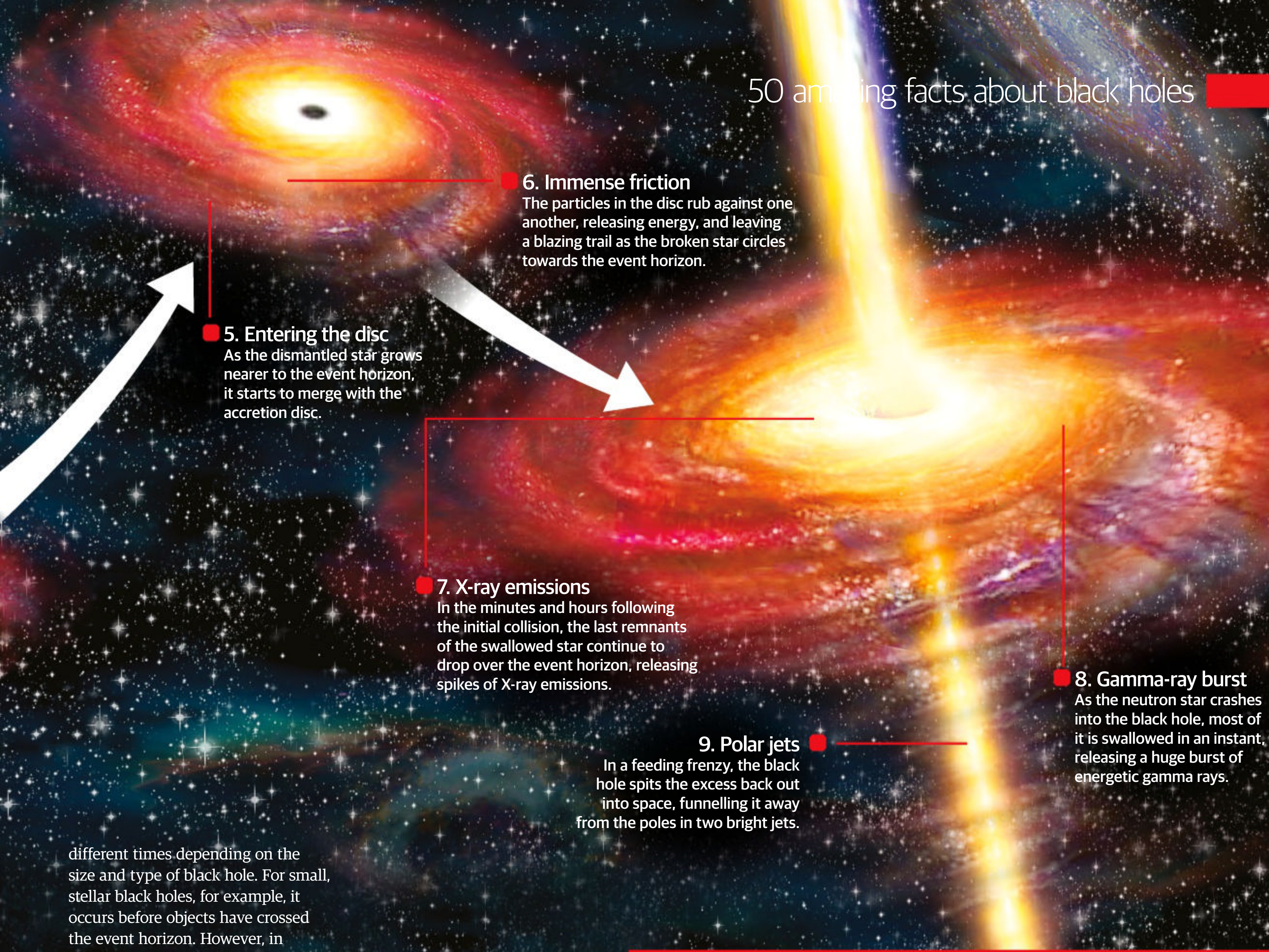
## 30 Objects are stretched like spaghetti as they approach a black hole

As an object gets closer to a black hole, the gravitational pull rises sharply. The parts of the object that are closest to the black hole experience stronger attraction than those farther away, causing them to accelerate faster. This stretches the object as the front moves more quickly than the back, drawing it out into a long filament in a process known as spaghettification.

The tidal forces around a black hole are strong enough that anything entering becomes stretched, from the largest stars, to the smallest atoms. When the stretching force exceeds the elastic limit of the material it starts to break apart, continuing to tear into smaller and smaller pieces, each being stretched out like spaghetti, until all that is left are the elementary particles. Spaghettification takes place at

## 31 When two black holes collide, they form one even more massive black hole

It is thought likely that the supermassive black holes at the centres of galaxies began to form early in the evolution of the universe. As matter condensed to form the first galaxies, it would have been much closer together, and small black holes would have been able to feast on dust, and gas, becoming truly massive in a very short space of time. Several 'intermediate black holes' are thought to have formed within clusters of stars, before sinking towards the centres of galaxies under the influence of each other's gravitational pull, collapsing in on one another to form the supermassive giants that we see today.



**6. Immense friction**
The particles in the disc rub against one another, releasing energy, and leaving a blazing trail as the broken star circles towards the event horizon.

**5. Entering the disc**
As the dismantled star grows nearer to the event horizon, it starts to merge with the accretion disc.

**7. X-ray emissions**
In the minutes and hours following the initial collision, the last remnants of the swallowed star continue to drop over the event horizon, releasing spikes of X-ray emissions.

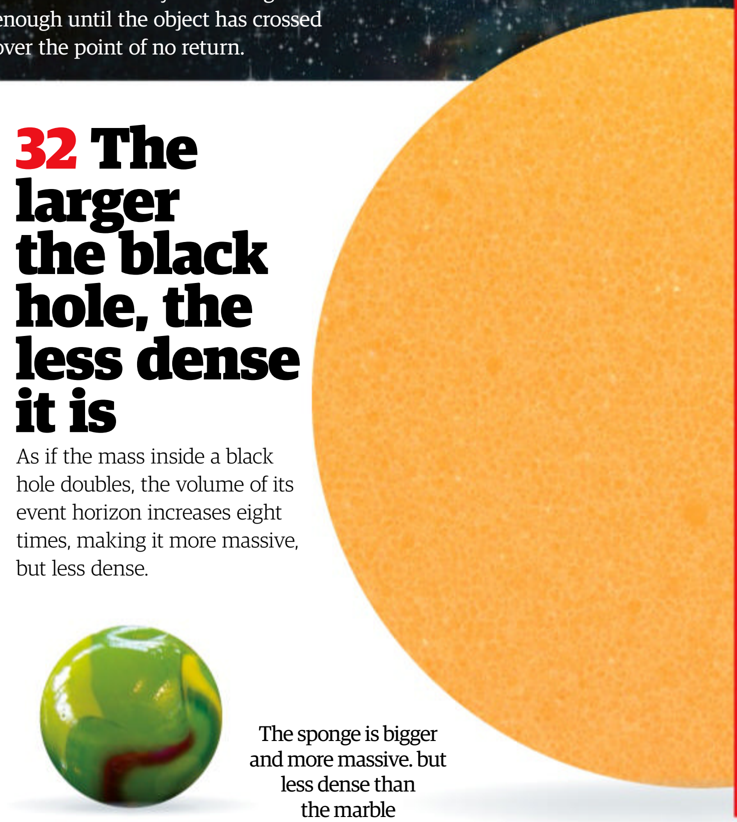
**8. Gamma-ray burst**
As the neutron star crashes into the black hole, most of it is swallowed in an instant, releasing a huge burst of energetic gamma rays.

**9. Polar jets**
In a feeding frenzy, the black hole spits the excess back out into space, funnelling it away from the poles in two bright jets.

different times depending on the size and type of black hole. For small, stellar black holes, for example, it occurs before objects have crossed the event horizon. However, in supermassive black holes, the tidal forces do not always become great enough until the object has crossed over the point of no return.

## 32 The larger the black hole, the less dense it is

As if the mass inside a black hole doubles, the volume of its event horizon increases eight times, making it more massive, but less dense.



The sponge is bigger and more massive, but less dense than the marble

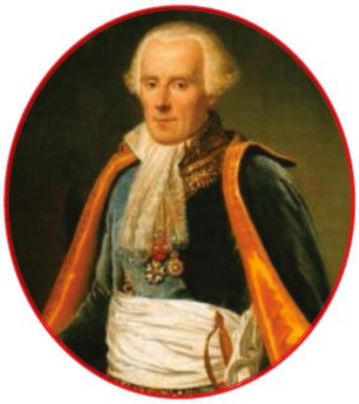
**Interview**

## 33 Even dwarf galaxies can harbour supermassive black holes

Prof Anil Seth, University of Utah, recently discovered a supermassive black hole at the centre of a dwarf galaxy

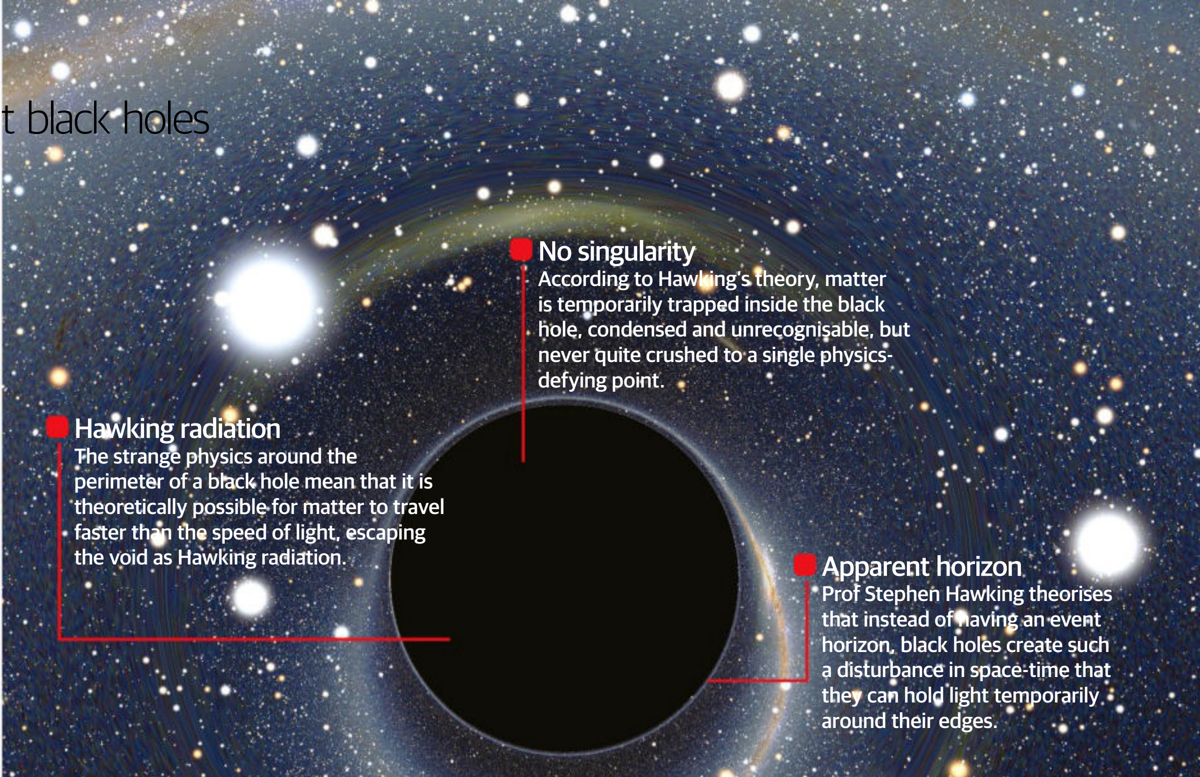
**What makes the supermassive black hole in the dwarf galaxy M60-UCD1 such an interesting find?**
"We think most big galaxies have supermassive black holes, but M60-UCD1 is much smaller and less massive than any other galaxy with a supermassive black hole. Supermassive black holes play an important role in how galaxies form, and this provides a new environment for us to find these objects. Currently we don't understand how supermassive black holes form because their formation happened so early in the universe."

**How did such a big black hole form in such a small galaxy?**
"M60-UCD1 got its name because it is just 22,000 light years from the giant elliptical galaxy M60 (this is closer than we are to the centre of our galaxy). We think that M60-UCD1 is in orbit around M60 and was once a much larger galaxy. When it passed close to the centre of M60, this bigger galaxy had its outer parts stripped away leaving just the dense core of stars and the black hole behind."



## 34 Black holes were first imagined in the 18th century

Scientists John Michell and Pierre-Simon LaPlace were the first to wonder about the existence of black holes, imagining that beyond a certain point, the gravity of a massive object must become so great that nothing can get away. The trouble was, according to Isaac Newton's theory of gravitation, light wouldn't be affected by gravity, because it has no mass. So, no matter how massive an object became, light should be able to escape. It wasn't until Einstein's theory of general relativity that the physics of black holes really started to make sense.



**No singularity**
According to Hawking's theory, matter is temporarily trapped inside the black hole, condensed and unrecognisable, but never quite crushed to a single physics-defying point.

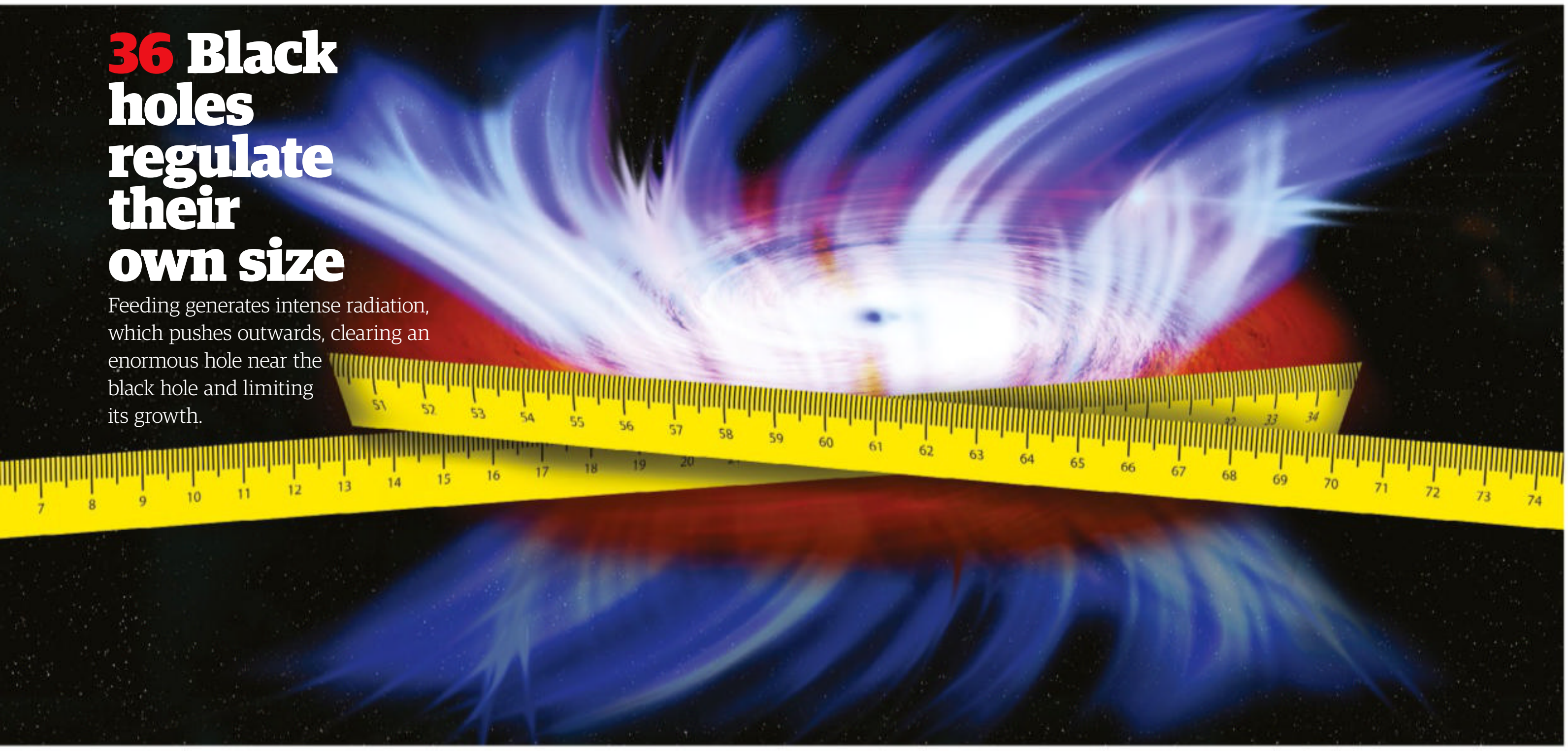
**Hawking radiation**
The strange physics around the perimeter of a black hole mean that it is theoretically possible for matter to travel faster than the speed of light, escaping the void as Hawking radiation.

**Apparent horizon**
Prof Stephen Hawking theorises that instead of having an event horizon, black holes create such a disturbance in space-time that they can hold light temporarily around their edges.

## 35 Black holes might not exist

In 2014, Stephen Hawking put forward a controversial theory about black holes: they don't exist – at least not in the way we imagine. The science of black holes is based on Einstein's theory of general relativity, but there are areas that don't quite make sense, like the event horizon.

According to Einstein, the point at which matter crosses over into a black hole is where it gets destroyed as it's spaghettified and pulled towards the singularity. However, according to quantum theory, the event horizon would actually be a 'firewall' of high-energy particles. Einstein's theory contradicts quantum theory, but Hawking proposes a new answer: the event horizon doesn't exist. He suggests that black holes are not bottomless pits from which nothing can return. Instead, they just temporarily hold and scramble matter, before releasing it back into the universe as radiation.



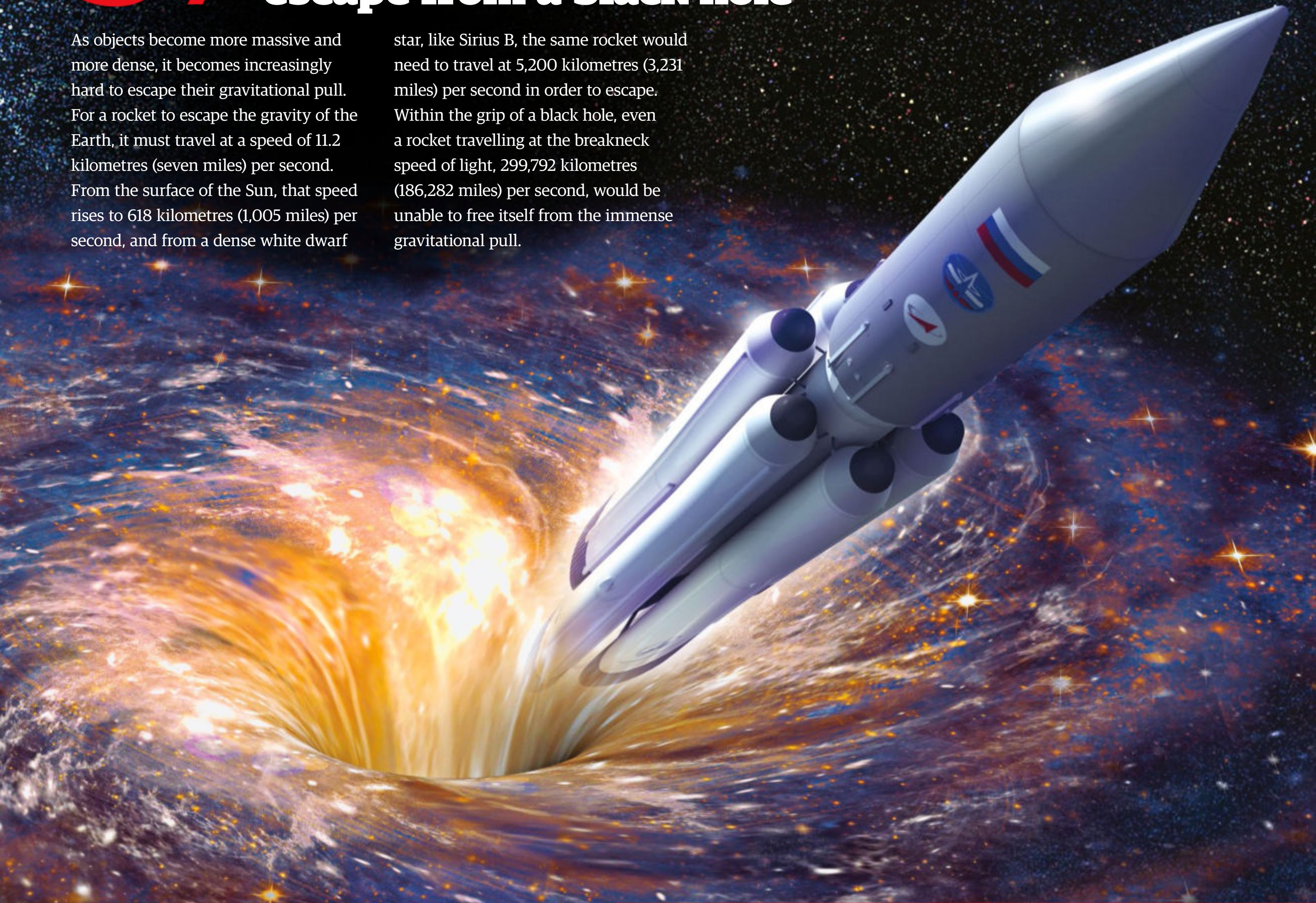
## 36 Black holes regulate their own size

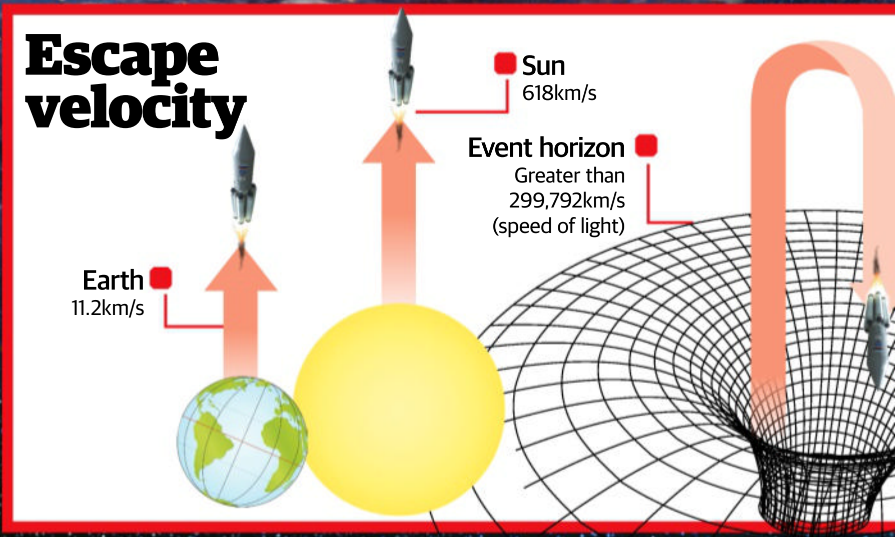
Feeding generates intense radiation, which pushes outwards, clearing an enormous hole near the black hole and limiting its growth.

# 37

# Even a rocket travelling at the speed of light could not escape from a black hole

As objects become more massive and more dense, it becomes increasingly hard to escape their gravitational pull. For a rocket to escape the gravity of the Earth, it must travel at a speed of 11.2 kilometres (seven miles) per second. From the surface of the Sun, that speed rises to 618 kilometres (1,005 miles) per second, and from a dense white dwarf star, like Sirius B, the same rocket would need to travel at 5,200 kilometres (3,231 miles) per second in order to escape. Within the grip of a black hole, even a rocket travelling at the breakneck speed of light, 299,792 kilometres (186,282 miles) per second, would be unable to free itself from the immense gravitational pull.





**Escape velocity**

## 38 Some can be very tiny

The smallest theoretical mass for a black hole is around 22 micrograms, a value known as the Planck mass.

## 39 The closest black hole is 6,070 light years away from Earth

The closest black hole to Earth is Cygnus X-1. Located on the Orion Spur of the Milky Way, it has the mass of about 15 Suns.

## 40 "Black holes have no hair"

This famous statement made by scientist John Wheeler describes the simplicity of black holes. Typically, they can be described by just three quantities: their mass, angular momentum and electric charge.

## 41 They halt local star formation

The largest and most active supermassive black holes often occur in the quietest galaxies. The radiation released as they feed stops the gas around them condensing to form stars.

## 42 The Sun could never become a black hole

To become a black hole, a star must be so massive that it completely collapses under its own gravitational pull. The Sun is much too small, and instead it will end its life as a white dwarf.

## 43 Black holes come in different sizes

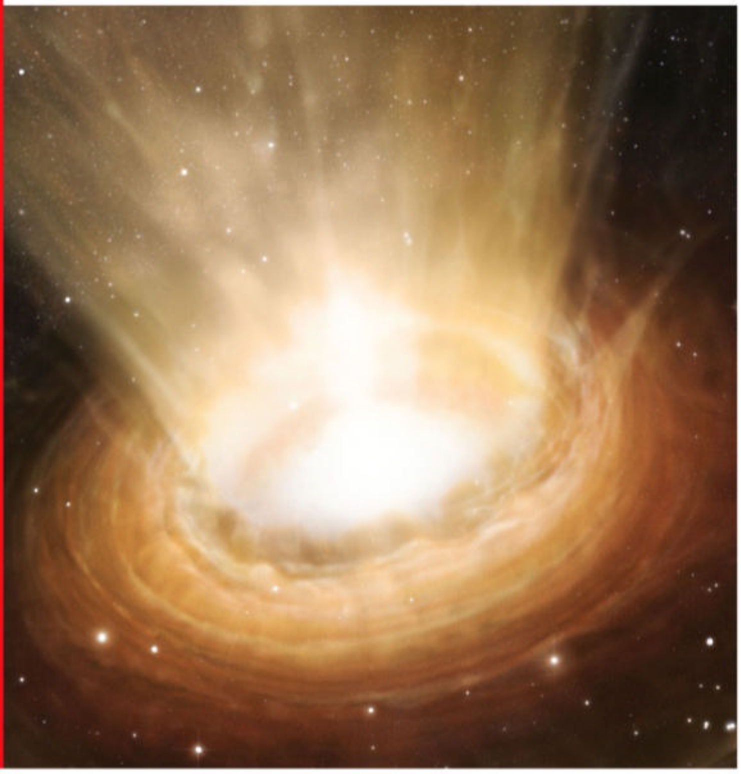
Stellar-mass black holes can measure just a few kilometres in diameter, whereas supermassive black holes can be the size of our solar system.

## 44

## There is a supermassive black hole at the centre of the Milky Way

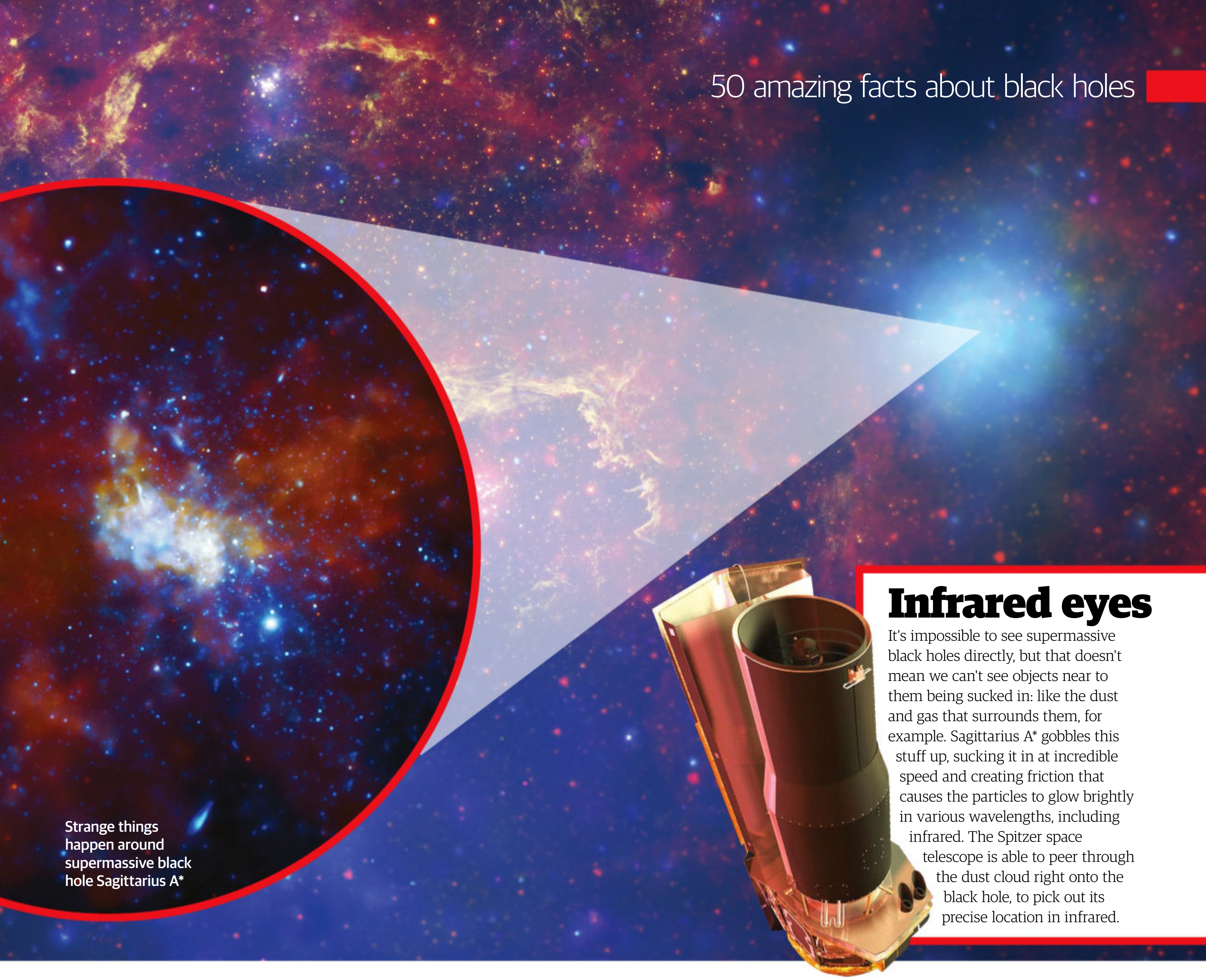
At the centre of the Milky Way, the stars move in strange circles. They hurtle towards a bright radio source, turn in a tight hairpin, and then race away again. Tracing the lines of their orbits reveals that they all overlap at a single point, known as Sagittarius A*.

The region is shrouded in a thick cloud of dust and gas, making it difficult to see, but in order to account for these highly elliptical orbits, astronomers have calculated that Sagittarius A* must contain around 4 million solar masses, compressed into a volume with a radius of about 25 million kilometres (15.5 million miles). In other words, it is a supermassive black hole.



## 45 Some black holes power the brightest objects in the universe

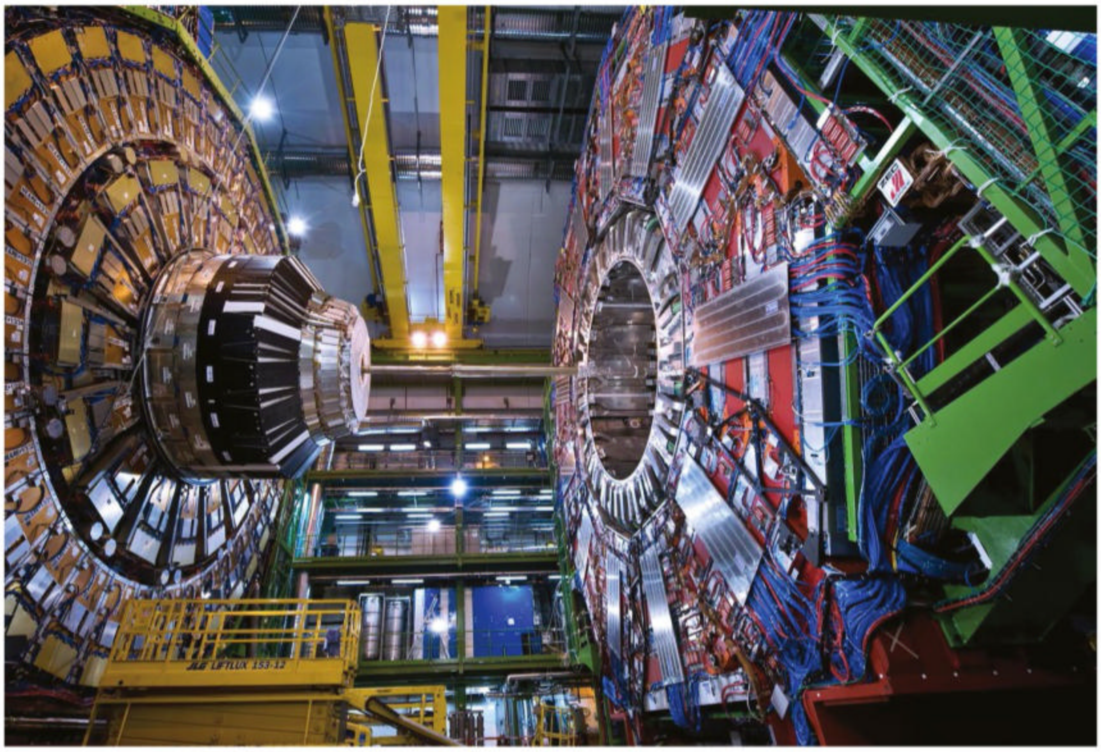
In the 1960s, US astronomer Allan Sandage noticed a very bright object in the distant sky. From Earth, it was as bright as a nearby star, but its vast distance meant that it must be emitting hundreds of times as much energy as all of the stars in the Milky Way combined. Dubbed quasars, these objects are among the brightest in the universe, and represent actively feeding supermassive black holes. Thousands have been identified, and each blazes brightly as matter tumbles on to its accretion disc, spewing X-rays and visible light into space, and producing energetic jets from its poles.



Strange things happen around supermassive black hole Sagittarius A*

## Infrared eyes

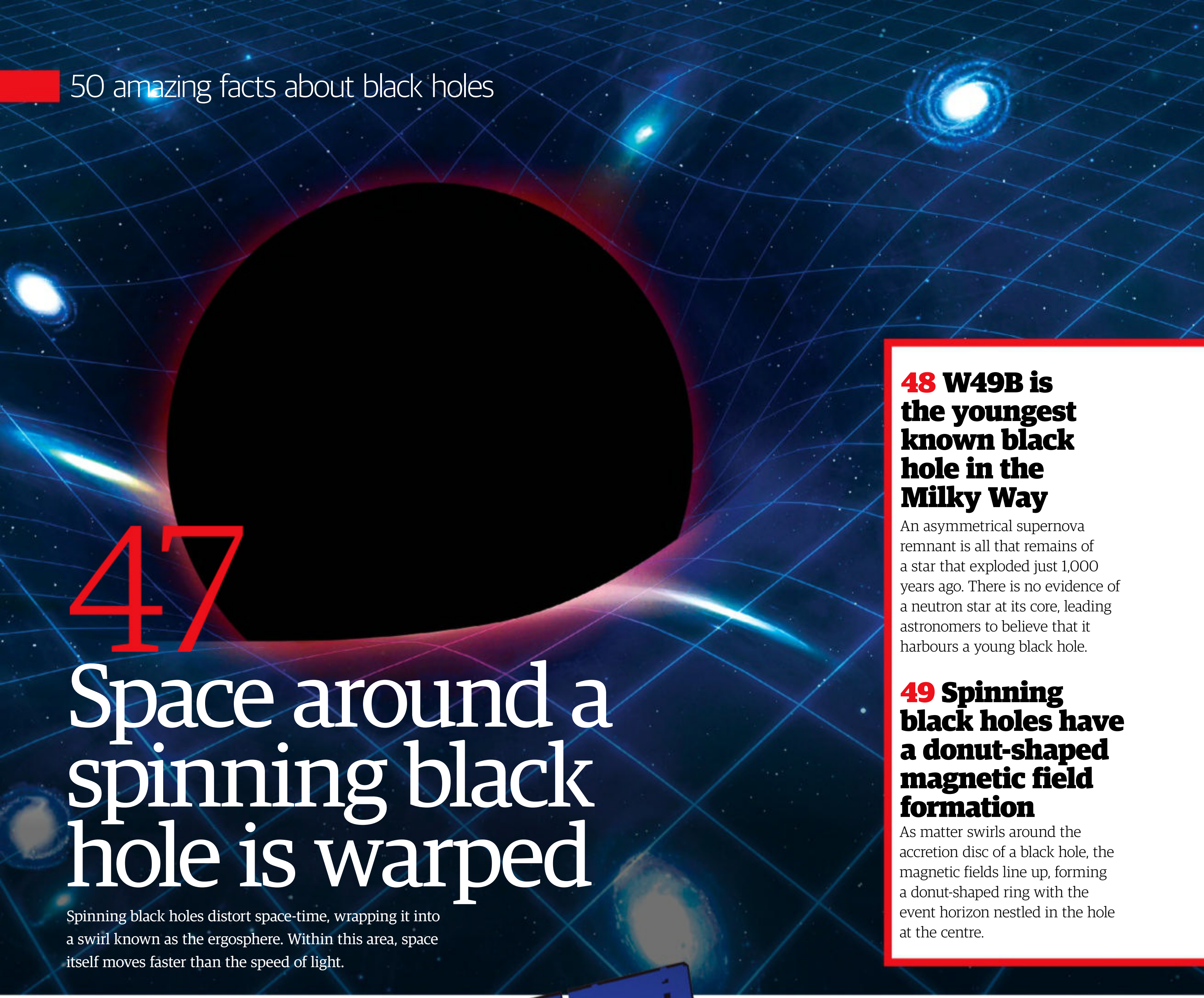
It's impossible to see supermassive black holes directly, but that doesn't mean we can't see objects near to them being sucked in: like the dust and gas that surrounds them, for example. Sagittarius A* gobbles this stuff up, sucking it in at incredible speed and creating friction that causes the particles to glow brightly in various wavelengths, including infrared. The Spitzer space telescope is able to peer through the dust cloud right onto the black hole, to pick out its precise location in infrared.



## 46 Particle accelerators could create micro black holes

When the Large Hadron Collider at CERN was switched on in 2008, there were concerns among scientists that the particles, travelling at close to the speed of light, could theoretically produce miniature black holes. So far, no such holes have been created, but it is definitely possible in theory.

Even if a micro black hole was created, there would be little to worry about. The black hole would be so small that it would take billions of years for it to consume just one gram of matter, and if Stephen Hawking is correct, and black holes do leak radiation, the tiny black hole would decay long before this ever happened.



## 47

## Space around a spinning black hole is warped

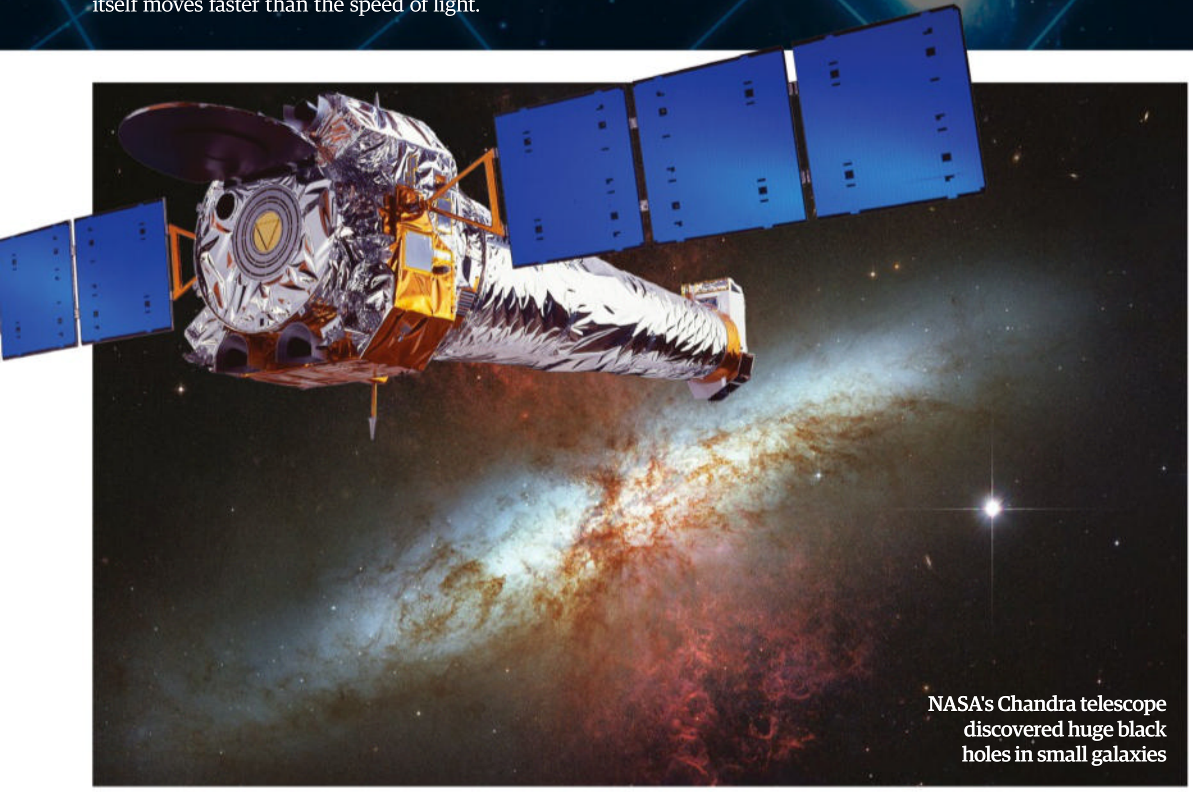
Spinning black holes distort space-time, wrapping it into a swirl known as the ergosphere. Within this area, space itself moves faster than the speed of light.

### 48 W49B is the youngest known black hole in the Milky Way

An asymmetrical supernova remnant is all that remains of a star that exploded just 1,000 years ago. There is no evidence of a neutron star at its core, leading astronomers to believe that it harbours a young black hole.

### 49 Spinning black holes have a donut-shaped magnetic field formation

As matter swirls around the accretion disc of a black hole, the magnetic fields line up, forming a donut-shaped ring with the event horizon nestled in the hole at the centre.



NASA's Chandra telescope discovered huge black holes in small galaxies

## 50 Smaller galaxies contain medium-sized black holes

It was originally thought that black holes only came in two sizes: stellar-mass black holes and supermassive black holes. However, researchers using data from NASA's Chandra X-Ray Observatory and Rossi X-Ray Timing Explorer (RXTE) telescopes were able to measure a medium-sized black hole in Messier 82 to be around 400 solar masses. Known as intermediate-mass black holes, these seeds of the most destructive objects in the universe contain between 100 and 10,000 times the mass of the Sun.

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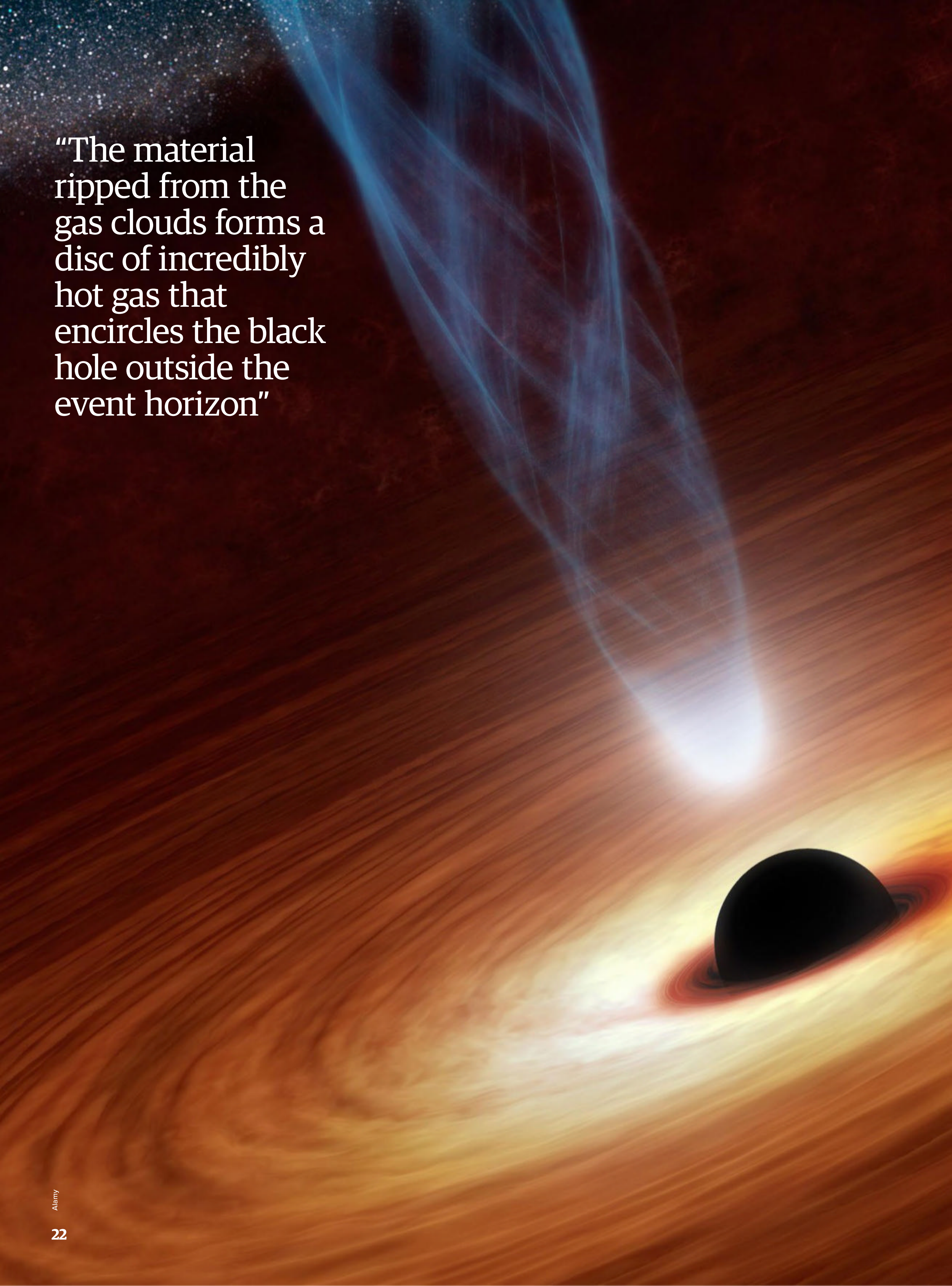

> “The material ripped from the gas clouds forms a disc of incredibly hot gas that encircles the black hole outside the event horizon”

Alamy

# Explaining Black Holes

## Unearth the science behind black holes and how they work

**24** The science of black holes
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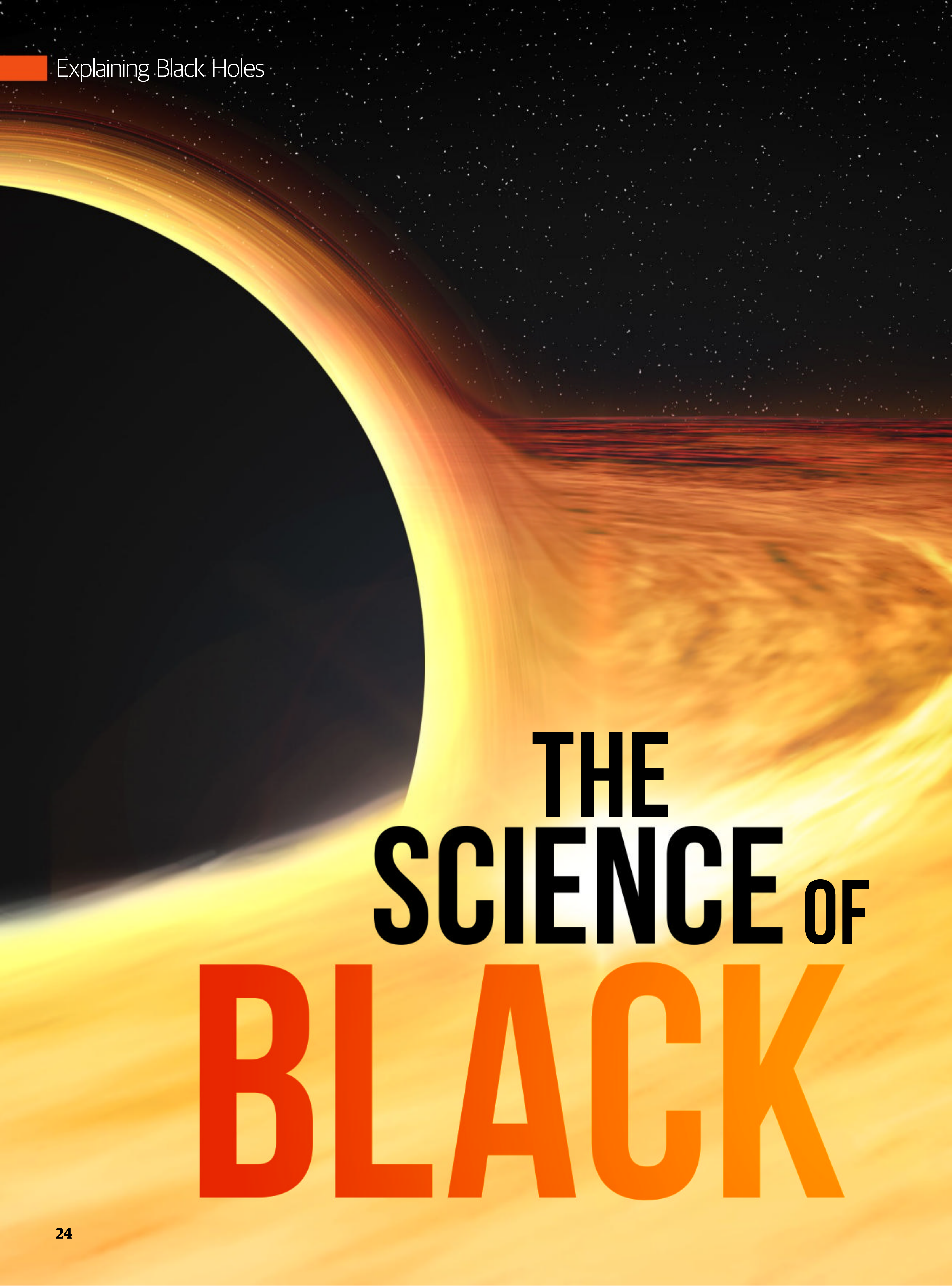
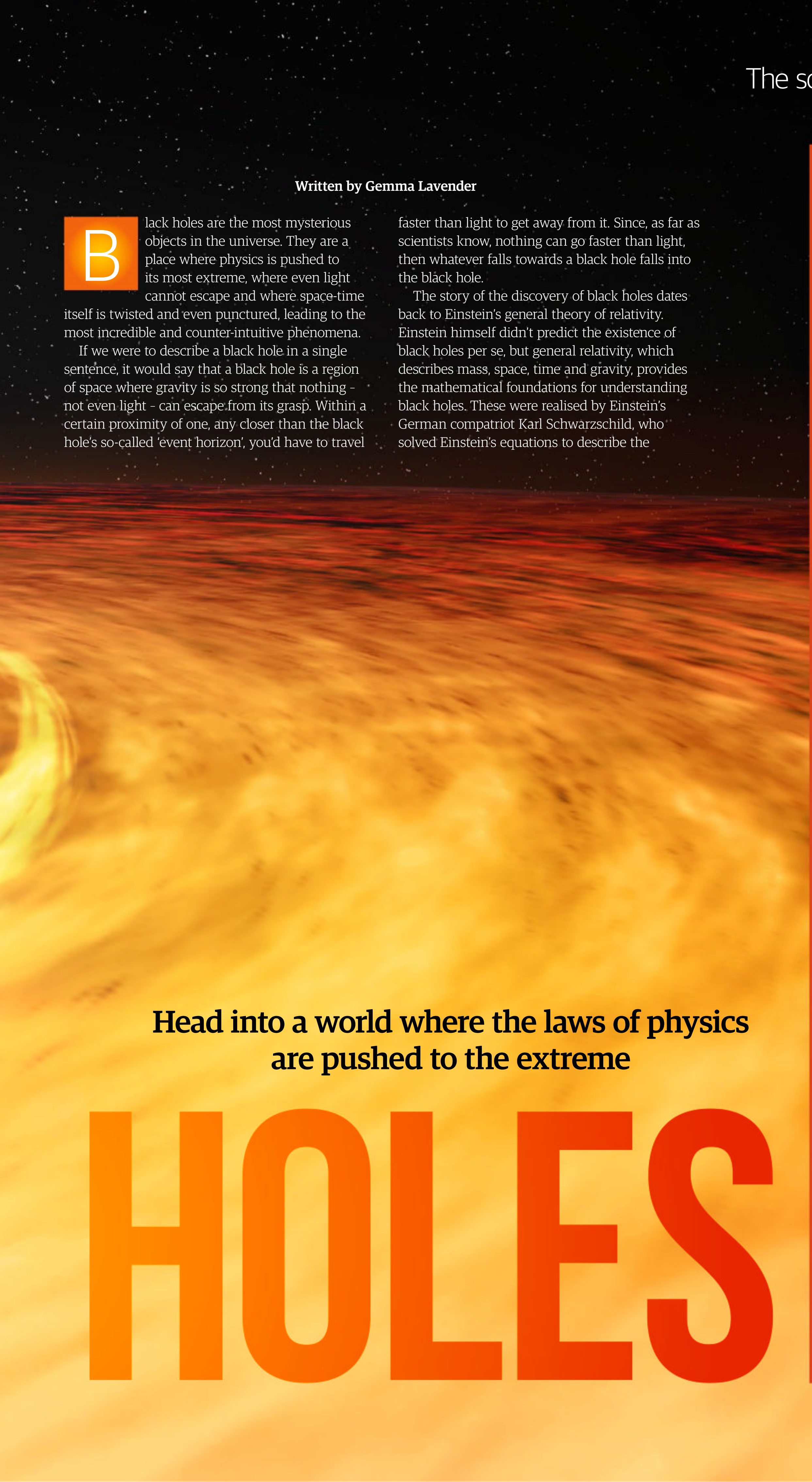


# THE SCIENCE OF BLACK



# HOLES

Head into a world where the laws of physics are pushed to the extreme

Written by Gemma Lavender

Black holes are the most mysterious objects in the universe. They are a place where physics is pushed to its most extreme, where even light cannot escape and where space-time itself is twisted and even punctured, leading to the most incredible and counter-intuitive phenomena.

If we were to describe a black hole in a single sentence, it would say that a black hole is a region of space where gravity is so strong that nothing - not even light - can escape from its grasp. Within a certain proximity of one, any closer than the black hole's so-called 'event horizon', you'd have to travel faster than light to get away from it. Since, as far as scientists know, nothing can go faster than light, then whatever falls towards a black hole falls into the black hole.

The story of the discovery of black holes dates back to Einstein's general theory of relativity. Einstein himself didn't predict the existence of black holes per se, but general relativity, which describes mass, space, time and gravity, provides the mathematical foundations for understanding black holes. These were realised by Einstein's German compatriot Karl Schwarzschild, who solved Einstein's equations to describe the

## BLACK HOLES BY NUMBERS

**299,792,458**

The velocity, in metres per second, that you would have to move at to escape from just outside an event horizon

**66,000,000,000**

The biggest black hole known to exist is many times more massive than our Sun

**0.2**

The fraction of a second that the chirp of gravitational waves from the first black hole merger to be detected lasted

**4,100,000**

The black hole at the centre of our galaxy is many times more massive than our Sun, which orbits it

**3**

The number of fundamental properties a black hole can possess; this is called the no-hair theorem

**8**

The number of telescopes around the world that joined forces to form the Event Horizon Telescope gravitational field around a non-rotating, spherical mass, and to determine the Schwarzschild radius, which is the size of a black hole's event horizon. In the 1960s New Zealand mathematician Roy Kerr solved Einstein's equations for a more realistic scenario: that of a black hole that is spinning.

We've already mentioned that light cannot escape a black hole, and the event horizon is its ultimate boundary of no return. Once something has crossed the event horizon's invisible boundary, it can never return from the black hole. Let's picture what is going on using an oft-mentioned analogy. Think of a rubber sheet, which we have to imagine as being the fabric of space-time for this analogy to work. If you want to try this out at home, a bedsheet held tight at each corner should suffice!

Place a marble onto the sheet. In our example, that's Earth. Notice how it causes the sheet to dip a little. In general relativity, that dip in the fabric of space-time is called a gravitational well – it represents Earth's gravitational field. Now put a tennis ball on the sheet, imagining that it's the Sun. You'll notice that it creates a bigger dip than the 'Earth', not necessarily because it is larger, but because it has more mass.

If you were to zip ball bearings past both the marble and the tennis ball, they'd need more energy – in other words, to be moving faster – to get past the tennis ball without falling into its steeper gravitational well.

## How black holes are made

The deaths of giant stars birth these behemoths

**1 Birth of a massive star**

Forming from the collapse of a cloud of gas and dust, some stars are born bigger, brighter and hotter than others, glowing a bright blue.

**2 Beginning of the end**

Massive stars use up their hydrogen fuel more quickly, after just a few million years, and when they can no longer maintain nuclear fusion in their core they begin to swell up, becoming a red supergiant.

> “Light cannot escape a black hole, and the event horizon is its ultimate boundary”

Now put a cannonball on the rubber sheet – if you're trying this at home you probably don't have a cannonball to hand, but see if you can use something suitably heavy. It will create a dip so steep that once any ball bearings you roll in its direction get too close to it, they always fall into the dip, and cannot get out no matter how fast they are moving. Around a real black hole, the event horizon is the distance from the black hole where the dip is so steep that not even light can move fast enough to escape. And that's why black holes are 'black', because they gobble up light.

There's so much more to tell about the story of black holes. How are they formed? Where do the things that fall into them go? What exists at the centre of a black hole? And what do black holes do in the centre of galaxies? Let's start with how they are formed. When our Sun, a star, reaches the end of its life in about 5 billion years, it will expand to become a red giant before gracefully puffing off

**3 The stellar core implodes**
When fusion reactions stop, the force of gravity causes the core to implode to form a compact neutron star. The surrounding layers of the star rebound off the neutron star core, exploding as a supernova.

**4 Gravitational collapse**
If the star – or more specifically its core – is massive enough, the neutron star will keep imploding, gravitationally collapsing all the way down to a single point of infinite mass: a black hole.

**5 Black hole mergers**
Black holes grow by accreting matter, or by colliding and merging with other black holes. When a merger takes place, it releases gravitational waves that scientists can detect.

## Famous black hole candidates

### Cygnus X-1

**Location:** 6,070 light years away

**Mass:** 21.2 Suns

A stellar-mass black hole orbiting a blue supergiant star. The black hole is stealing gas from the star, forming an accretion disc which occasionally outbursts in X-rays.

### Sagittarius A*

**Location:** 26,000 light years away

**Mass:** 4.1 million Suns

The supermassive black hole at the centre of our Milky Way galaxy. It is generally inactive, with only modest X-ray outbursts as it consumes small gas clouds.

### Messier 87's black hole

**Location:** 54 million light years away

**Mass:** 6.5 billion Suns

The first black hole to be imaged right down to the event horizon by the Event Horizon Telescope, which saw the black hole's 'shadow' on the surrounding accretion disc.

### GW 150914

**Location:** 1.4 billion light years away

**Mass:** 62 Suns

The product of the first-ever black hole merger detected from its gravitational waves, it formed when a 35-solar-mass black hole collided with a 30-solar-mass black hole. The extra three solar masses were converted into gravitational-wave energy.

### 3C 273

**Location:** 2.4 billion light years away

**Mass:** 886 million Suns

The first quasar discovered, the black hole at its heart is hungrily guzzling gas, producing an incredibly bright accretion disc and a jet moving at almost the speed of light.

© EHT Collaboration

its outer layers to form a planetary nebula, leaving behind its small, hot core: a white dwarf. Stars more than eight times the mass of the Sun, however, bow out more explosively. Their huge mass ultimately causes the core to collapse due to the internal pull of its own gravity, while the rest of the star goes supernova. As the outer parts of the star explode, the collapsing core condenses to become a neutron star, which is so tightly packed that it contains as much - or more - mass as the Sun, but is only 20 kilometres (12.4 miles) or so across. If the star is massive enough, at least 30 to 40 times the mass of the Sun, then the collapse will continue past the neutron star stage, imploding and collapsing down to a point of infinite density, which is the 'singularity' at the heart of a black hole.

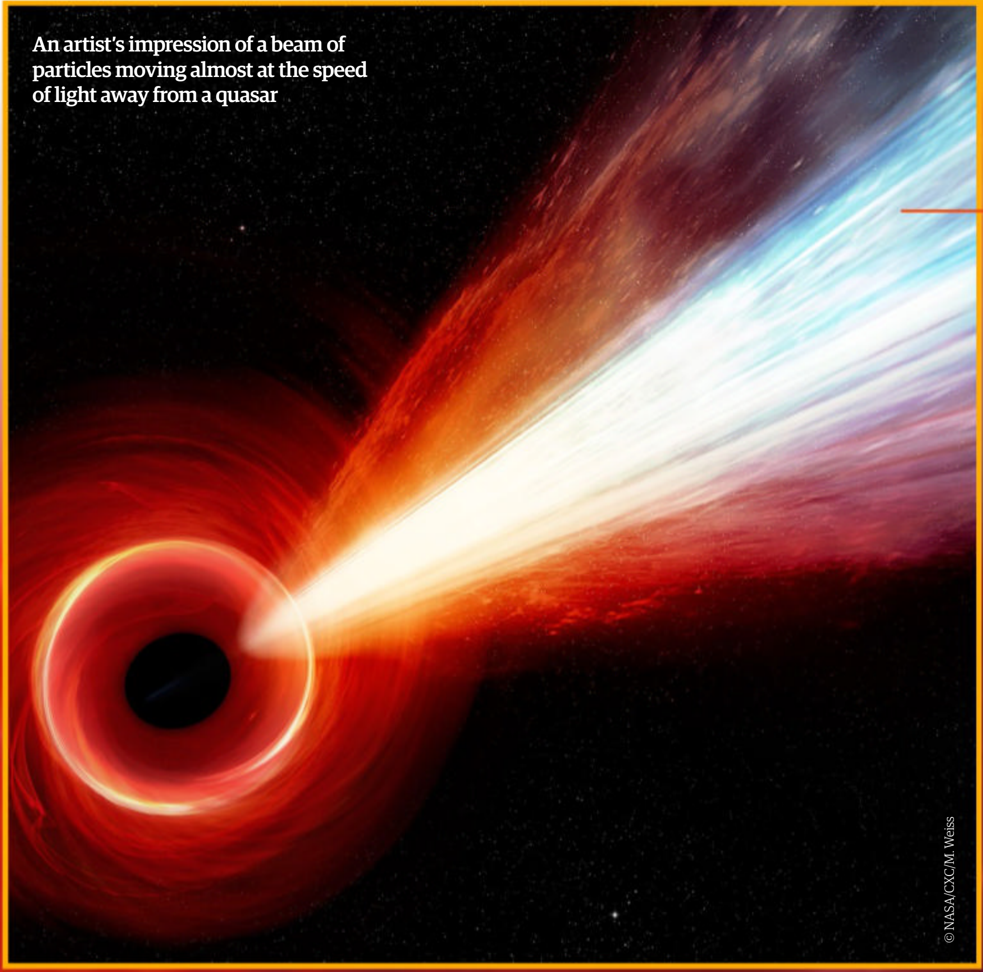
> "Collapse will continue past the neutron star stage, imploding and collapsing down to a point of infinite density"

In mathematics, singularities are calculations that tend to infinity, usually because of some error - some gap in our knowledge needed to fully complete the equation. This also describes the black hole singularity in the sense that we don't know the necessary physics to figure the singularity out. That's because at the microscopic scale of the black hole singularity, we enter the world of quantum physics, and scientists do not yet have a theory of quantum gravity. Until we do, scientists won't have the tools to be able to mathematically describe a black hole singularity.

Not that any of this prevents astronomers from learning more about what occurs outside the event horizon, where light still escapes. Some black holes can grow to be millions, or even billions of times more massive than our Sun - in case you're wondering, our Sun has a mass of 1.9 x $10^{30}$ kilograms, or 1.9 million trillion trillion kilograms.

Astronomers aren't entirely sure how black holes grow to be 'supermassive' like this - supermassive black holes might be the result of lots of mergers of smaller black holes created by supernovae, or maybe they were formed by giant clouds of gas that existed when the universe was very young, which underwent a dramatic gravitational collapse and imploded to form a massive black hole.

However they formed, supermassive black holes are found at the centres of most giant galaxies. For example, our home galaxy, the Milky Way, has a supermassive black hole at its heart called Sagittarius A*, and it has a mass 4.1 million times



An artist's impression of a beam of particles moving almost at the speed of light away from a quasar

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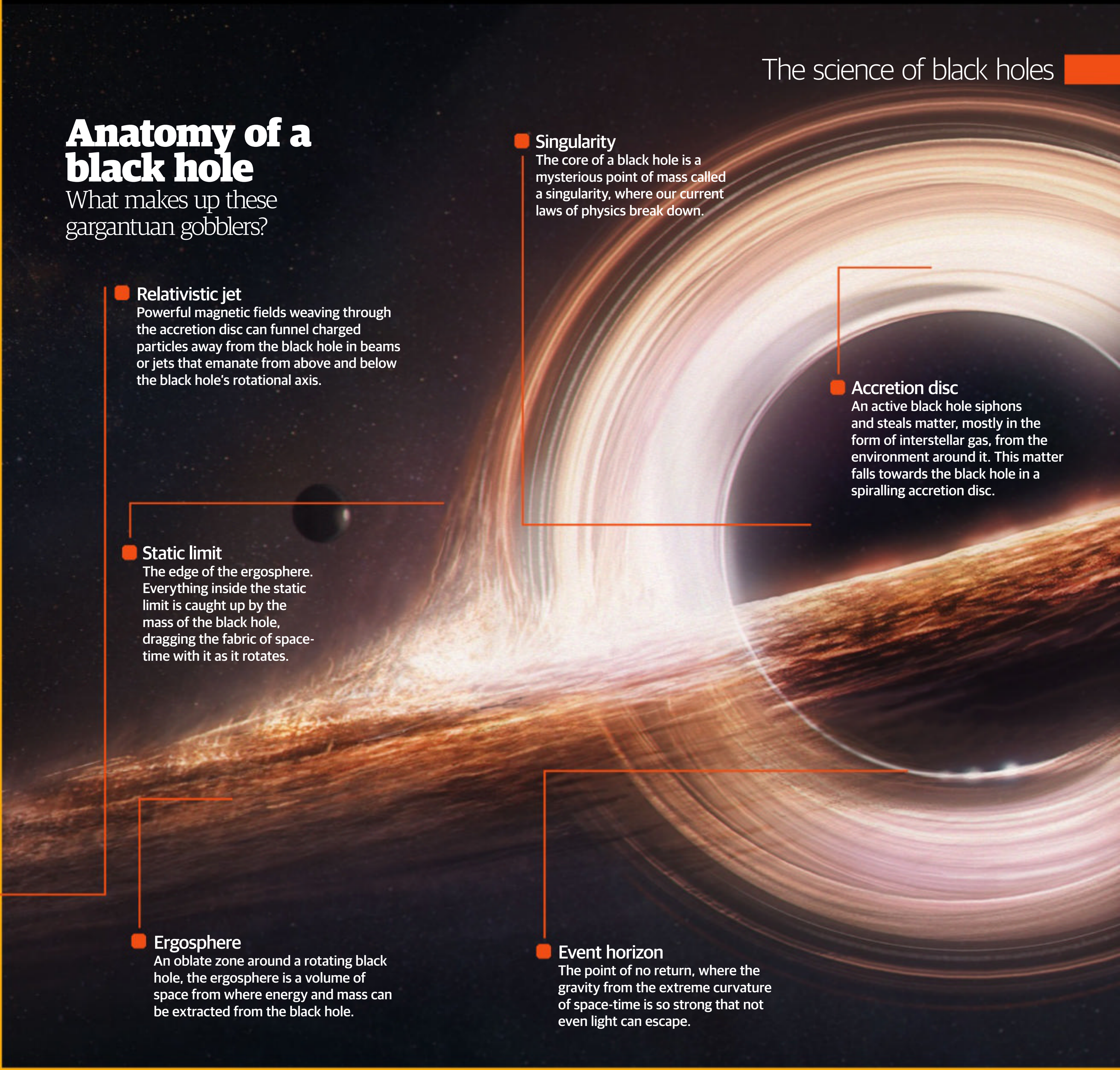
# Anatomy of a black hole

What makes up these gargantuan gobblers?



**Singularity**
The core of a black hole is a mysterious point of mass called a singularity, where our current laws of physics break down.

**Relativistic jet**
Powerful magnetic fields weaving through the accretion disc can funnel charged particles away from the black hole in beams or jets that emanate from above and below the black hole's rotational axis.

**Accretion disc**
An active black hole siphons and steals matter, mostly in the form of interstellar gas, from the environment around it. This matter falls towards the black hole in a spiralling accretion disc.

**Static limit**
The edge of the ergosphere. Everything inside the static limit is caught up by the mass of the black hole, dragging the fabric of space-time with it as it rotates.

**Ergosphere**
An oblate zone around a rotating black hole, the ergosphere is a volume of space from where energy and mass can be extracted from the black hole.

**Event horizon**
The point of no return, where the gravity from the extreme curvature of space-time is so strong that not even light can escape.

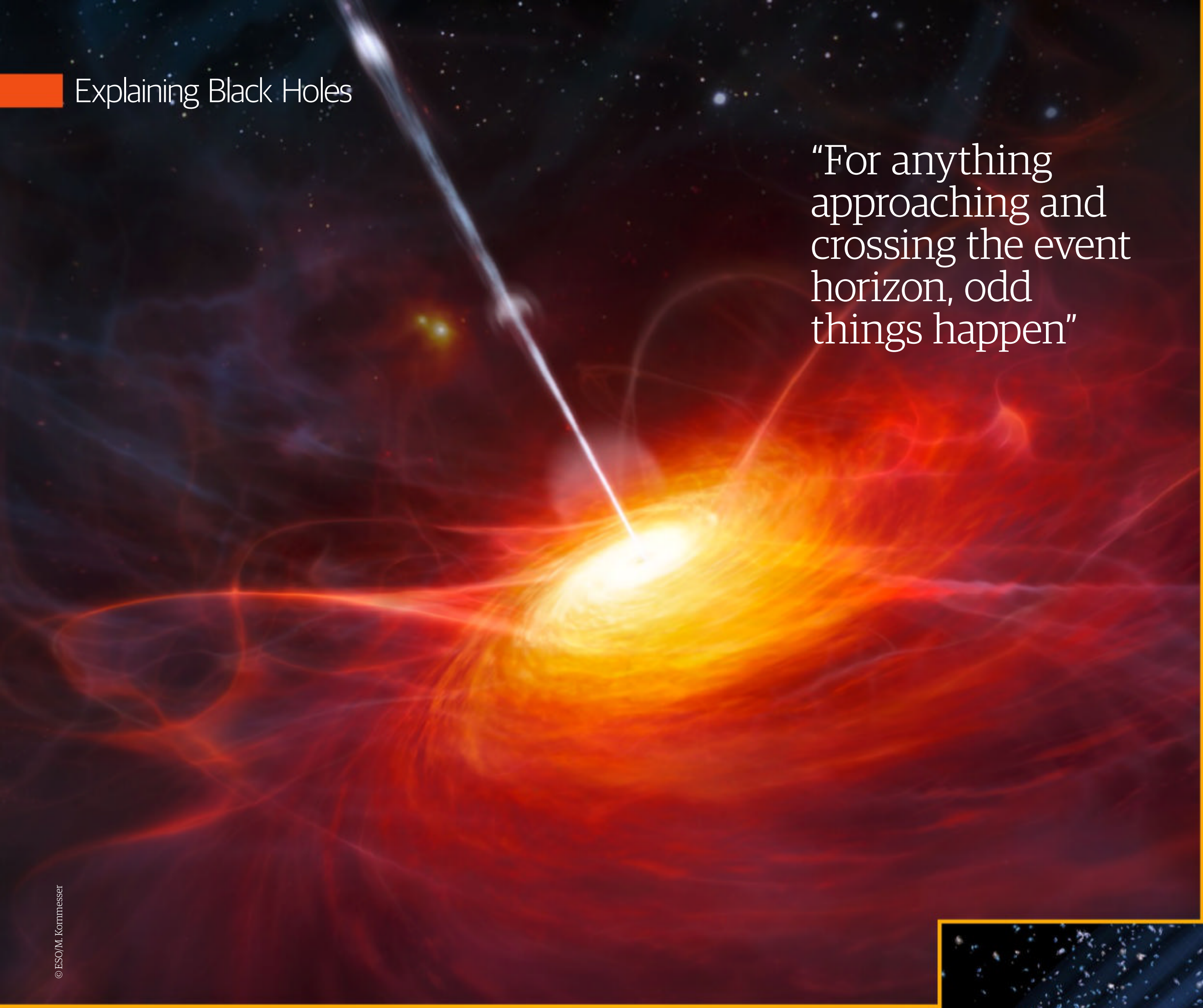
greater than the Sun's mass. The huge, powerful gravitational well of a supermassive black hole means that they can pull in a lot of surrounding material - gas and dust clouds, asteroids, comets and sometimes whole stars. This material gets ripped apart by the gravitational tidal forces being wielded by the black hole, and leads to a phenomenon known as 'spaghettification'.

Imagine an unfortunate astronaut floating too close to a black hole feet first. The tidal forces are so great that the gravity pulling on the astronaut's feet will be far stronger than the gravity pulling on their head. This would have the effect of stretching them out to the point that they would be pulled into strings of their respective atoms and molecules. Fortunately no astronaut has ever fallen into a black hole, but plenty of gas clouds have, and they get spaghettified too. We can see the consequences of these gas clouds being torn apart around active black holes - the material ripped from the gas clouds forms a disc of incredibly hot gas that encircles the black hole outside the event horizon.

Astronomers call these 'accretion discs' because the gas is said to be accreting onto the black hole. Friction between the atoms and molecules in the disc, which can be moving around the black hole at high speed, causes the gas to heat up and shine brightly. While a black hole itself is dark, the environment just outside an active black hole's event horizon can be highly luminous. Furthermore, the disc is rife with powerful magnetic fields emanating from the black hole, and these can funnel charged particles in the disc towards the black hole's rotational axis.

The energies are so great that these particles are then magnetically beamed away from the black hole in visible jets that move at almost the speed of light. These jets - like the accretion discs they originate from - are incredibly bright, and when our line of sight is looking almost straight down one of these jets, we see a luminous object called a quasar. When we happen to be looking directly down the jet it is even more luminous, and we call that a blazar. Regardless of what astronomers call it, the phenomenon is the same - a monstrous black hole that is spitting out a meal.

Some of the gas in the accretion disc does, however, eventually find itself spiralling into



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“For anything approaching and crossing the event horizon, odd things happen”

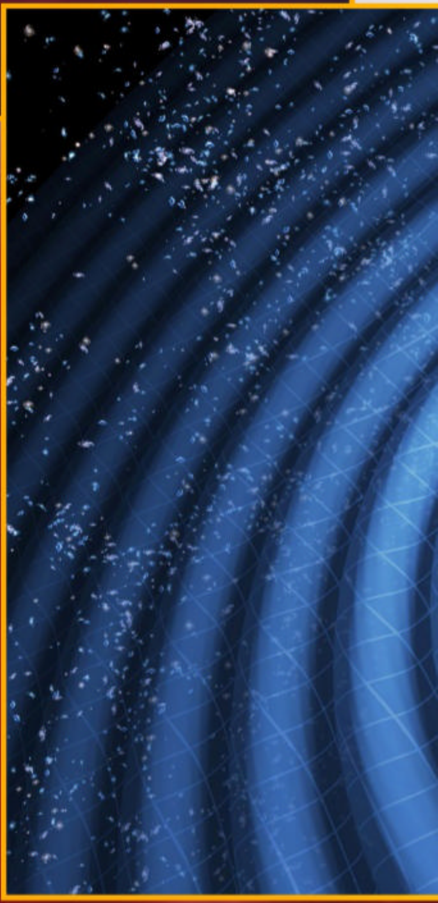
**Above:** Artist’s depiction of a quasar, a hungry black hole with a hot accretion disc, beaming out jets of radiation

the black hole. For anything approaching and crossing the event horizon, odd things happen. The warping of space-time by the mass of the black hole is so great here that something called gravitational time dilation occurs. As you approach the event horizon, time begins to run differently compared to the clocks belonging to observers who are watching from a distance - for example those watching a black hole with telescopes. A distant observer would see time stand still at the event horizon, and any astronaut crossing the event horizon would appear nearly frozen in time. The astronaut, however, would not perceive time slowing down. Assuming they’ve somehow survived spaghettification, time will seem to proceed normally to them. It’s just one of the weird consequences of Einstein’s theory.

“It turns out that black holes aren’t truly black. Black holes can actually radiate particles, and even light”

And what of material that does fall irrevocably into a black hole? Where does it go, and can it ever come back out again? Stephen Hawking asked this question, and even made a famous bet about it.

It turns out that black holes aren’t truly black. Stephen Hawking became famous for the concept of Hawking radiation, which was the realisation that black holes can actually radiate particles, and even light. The secret lies in quantum field theory, which is a way of saying that on the quantum level, space is continuously fizzing with energy, spontaneously producing pairs of ‘virtual’ particles. One is made of matter, and the other of antimatter, such as a positron and an electron. They’re described as ‘virtual’ because they usually instantly annihilate one another - as matter and antimatter do when they come into contact with one another - so they’re not in existence for very long. Hawking realised that pairs of virtual particles coming into existence on the edge of the event horizon can be split up. One falls into the black hole while the other



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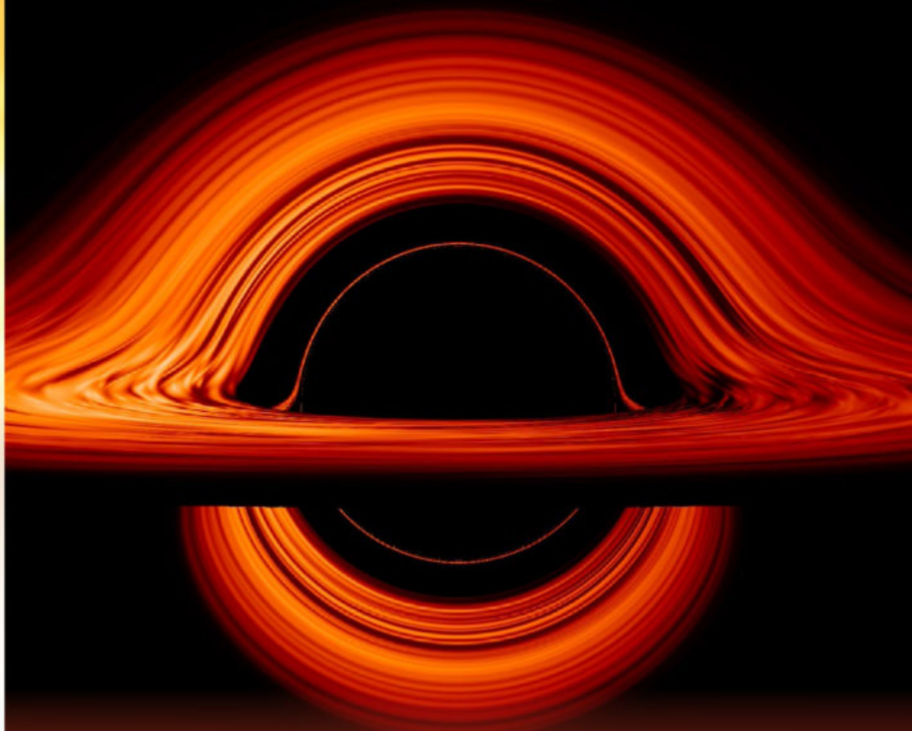
- if it has enough energy - can race away into space and escape the black hole's pull. Since the escaping particle has lost its anti-partner, it doesn't annihilate, surviving to become a 'real' particle.

Since the energy of the quantum field is drawn from the black hole's mass, the escaping particle is essentially running off with some of the mass of the black hole. Over the course of trillions and trillions of years, even the most supermassive black holes will begin to evaporate through the release of Hawking radiation.

Once a black hole evaporates, what happens to all the information of everything that went into it? This is the source of the black hole information paradox, which became the focus of Hawking's famous bet with fellow physicists Kip Thorne and John Preskill. They would often make scientific bets with one another, and in this particular case Hawking and Thorne bet Preskill that information inside a black hole is not preserved. In 2004 Hawking conceded the bet - though Kip Thorne hasn't yet - by agreeing that black holes do preserve information through Hawking radiation, giving Preskill a baseball encyclopaedia 'made for the storage and retrieval of information'.

Black holes fascinate us because they are so far out of our everyday experience, and there is still so much we don't know about them. When the Event Horizon Telescope took the very first image of a black hole's event horizon around the black hole at the centre of the giant galaxy Messier 87, which is 53 million light years away, it made the front page of newspapers and was all over the internet. Who knows what new and improved telescopes will discover about black holes in the future?



**Right:** A simulation of a black hole showing how its gravity warps the light of the accretion disc around it

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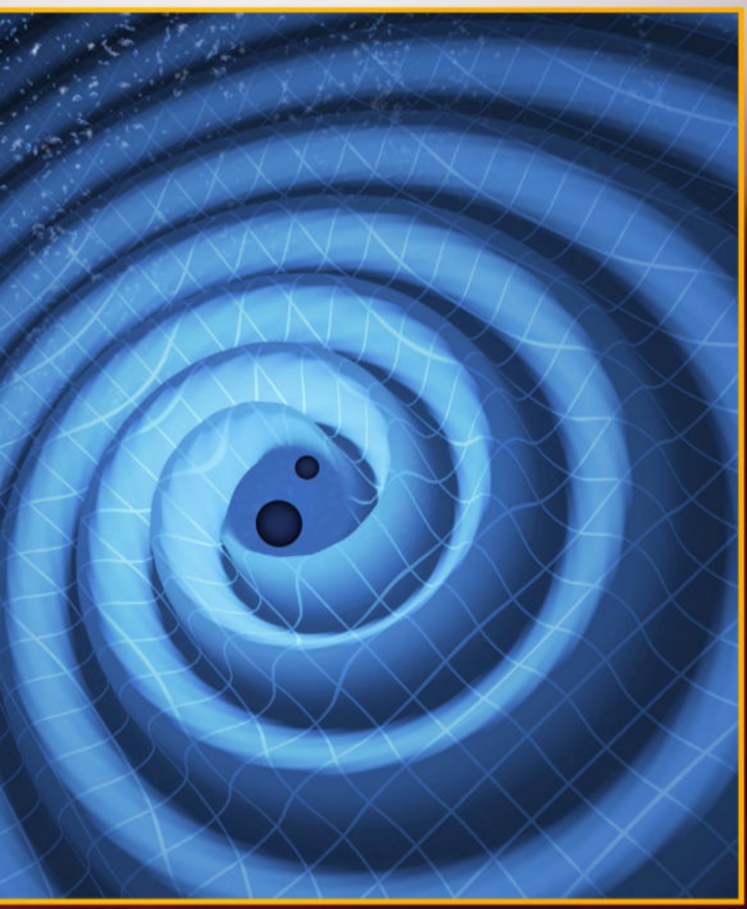


**Below:** Two black holes on the verge of merging release gravitational waves as they spiral towards each other

# Different kinds of black hole

FACT 1

### A small black hole

Despite packing in more than 4 million times the mass of our Sun, the black hole at the centre of our galaxy is no larger than the Solar System.

FACT 2

### The closest black hole

The nearest known black hole candidate is found in the triple star system HR 6819, which is 1,120 light years away.

FACT 3

### Most massive black hole

The heaviest of heavyweights is the supermassive black hole found in the quasar TON 618, which has a mass 66 billion times greater than our Sun.

FACT 4

### Runaway black holes

Galaxies often collide, and when they do their respective supermassive black holes also eventually merge, which can give the product of the merger a kick, causing it to escape its galaxy all together.

FACT 5

### Miniature black holes

Some theories suggest that the Big Bang created a horde of microscopic black holes, with masses ranging from 100 millionths of a kilogram up to the mass of a small asteroid. But these would have all evaporated through Hawking radiation.

# What happens at the centre of a black hole?

## All of the possibilities are very weird

**Reported by Paul Sutter**

The singularity at the centre of a black hole is the ultimate no man's land: a place where matter is compressed down to an infinitely tiny point, and all conceptions of time and space completely break down. And it doesn't really exist. Something has to replace the singularity, but we're not exactly sure what.

Let's explore some possibilities.

### Planck stars

It could be that deep inside a black hole, matter doesn't get squished down to an infinitely tiny point. Instead, there could be a smallest possible configuration of matter, the tiniest possible pocket of volume.

This is called a Planck star, and it's a theoretical possibility envisioned by loop quantum gravity, which is itself a highly hypothetical proposal for creating a quantum version of gravity. In the world of loop quantum gravity, space and time are quantised - the universe around us is composed of tiny discrete chunks, but at such an incredibly tiny scale that our movements always appear smooth and continuous.

This theoretical chunkiness of space-time provides two benefits. Firstly, it takes the dream of quantum mechanics to its ultimate conclusion, explaining gravity in a natural way. And secondly, it makes it impossible for singularities to form inside black holes.

As matter squishes down under the immense gravitational weight of a collapsing star, it meets resistance. The discreteness of space-time prevents matter from reaching anything smaller than the Planck length (around 1.68 times 10^-35 meters, so... small). All the material that has ever fallen into the black hole gets compressed into a ball that's not much bigger than this. It's perfectly microscopic, but definitely not infinitely tiny.

This resistance to continued compression eventually forces the material to un-collapse (explode), making black holes only temporary objects. But because of the extreme time dilation effects around black holes, from our perspective in the outside universe it takes billions, even trillions, of years before they go boom. So we're all set for now.

### Gravastars

Another attempt to eradicate the singularity - one that doesn't rely on untested theories of quantum gravity - is known as the gravastar. It's such a theoretical concept that spell checkers don't even recognise the word.

The difference between a black hole and a gravastar is that instead of a singularity, the gravastar is filled with dark energy. Dark energy is a substance that permeates space-time, causing it to expand outward. It sounds like sci-fi, but it's real: dark energy is currently in operation in the larger cosmos, causing our entire universe to accelerate in its expansion.

As matter falls onto a gravastar, it isn't able to actually penetrate the event horizon (due to all that dark energy on the inside) and therefore just hangs out on the surface. But outside that surface, gravastars look and act like normal black holes.

However, recent observations of merging black holes with gravitational wave detectors have potentially ruled out the existence of gravastars, because merging gravastars will give a different signal than merging black holes, and outfits like the Laser Interferometer Gravitational-Wave Observatory and Virgo are getting more examples by the day. While gravastars aren't exactly a no-go in our universe, they are definitely on thin ice.

### Let's go for a spin

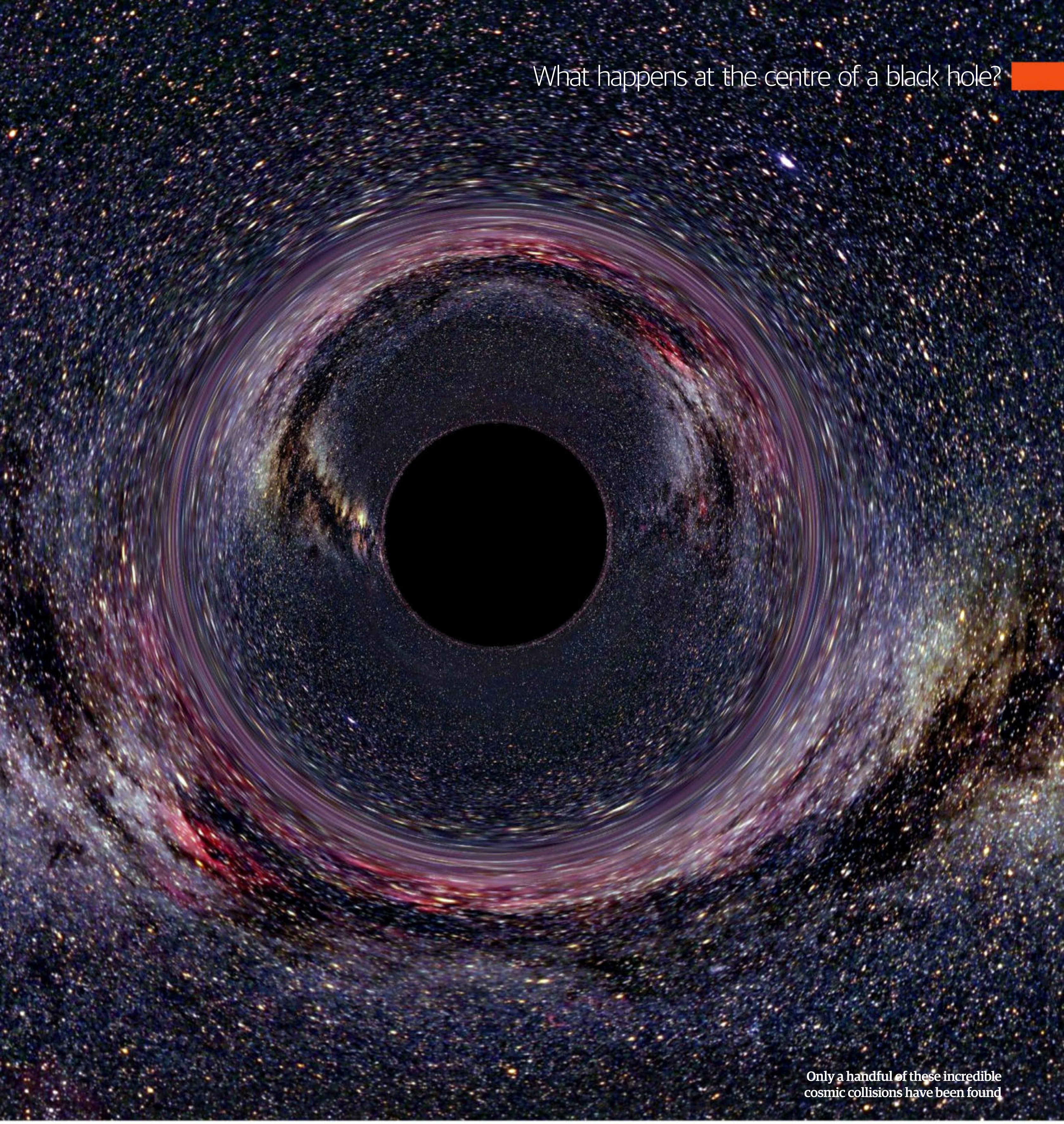
Planck stars and gravastars may have awesome names, but the reality of their existence is in doubt. So maybe there's a more mundane explanation for singularities, one that's based on a more nuanced - and realistic - view of black holes in our universe.

The idea of a single point of infinite density comes from our conception of stationary, non-rotating, uncharged, rather boring black holes. Real black holes are much more interesting characters, especially when they spin.

The spin of a rotating black hole stretches the singularity into a ring. And according to the maths of Einstein's theory of general relativity (which is

Getty Images

> "The singularity, stretched into a ring, is rotating at such a fantastic pace that it has incredible centrifugal force"



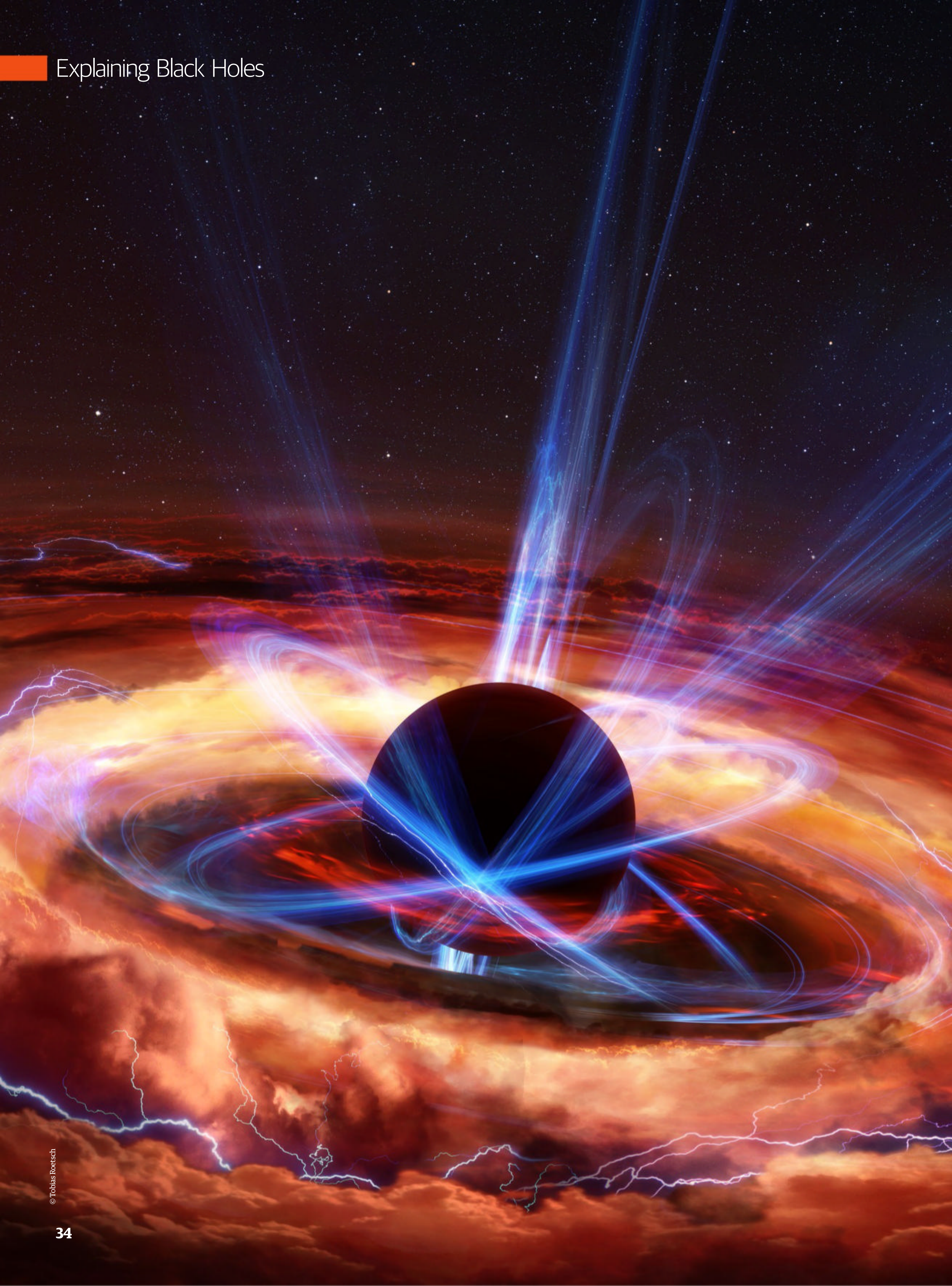
Only a handful of these incredible cosmic collisions have been found

the only maths we've got), once you pass through the ring singularity, you enter a wormhole and pop out through a white hole (the polar opposite of a black hole, where nothing can enter and matter rushes out at the speed of light) into an entirely new and exciting patch of the universe.

One challenge: the interiors of rotating black holes are catastrophically unstable. And this is according to the very same maths that leads to the prediction of the traveling-to-a-new-universe stuff. The problem with rotating black holes is that… well, they rotate. The singularity, stretched into a ring, is rotating at such a fantastic pace that it has incredible centrifugal force. And in general relativity, strong enough centrifugal forces act like antigravity: they push, not pull.

This creates a boundary inside the black hole, called the inner horizon. Outside this region, radiation is falling inward towards the singularity, compelled by the extreme gravitational pull. But radiation is pushed by the antigravity near the ring singularity, and the turning point is the inner horizon. If you were to encounter the inner horizon, you would face a wall of infinitely energetic radiation – the entire past history of the universe, blasted into your face in less than a blink of an eye. The formation of an inner horizon sows the seeds for the destruction of the black hole. But rotating black holes certainly exist in our universe, so that tells us that our maths is wrong and something funky is going on.

What's really happening inside a black hole? We don't know – and we may never know.



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# STRANGEST STAR IN THE UNIVERSE

Black holes might be collapsing stars that are exploding in slow motion

**Reported by Jonathan O'Callaghan**

What happens inside a black hole? That is a question that has long plagued astronomers, with numerous theories put forward, and numerous problems. Black holes have a gravitational pull so strong that nothing, not even light, can escape. This leads to a problem known as the 'information paradox' where information could disappear forever inside a black hole, something that doesn't hold up against our laws of physics. But an emerging theory put forward a few years ago proposes an unusual solution to this problem: that black holes are not what we think, and instead contain an object known as a 'Planck star' - collapsing stars rebounding in slow motion that, over time, emerge from view.

The idea of Planck stars was proposed in a paper by Carlo Rovelli from the University of Marseille in France and Francesca Vidotto, then of Radboud University Nijmegen in the Netherlands, in 2014. The two astronomers suggested that at the core of the black hole

## What we think we know about Planck stars

### They are remnants of dead stars

Planck stars are thought to be the remnant cores that are left behind after very massive stars run out of fuel and collapse at the end of their lives.

### They are stuck in slow motion

As the star collapses, the intense forces of gravity cause time dilation to occur – from our point of view the collapse is slow, but it's actually very fast.

### Event horizons are the outer edge of the collapse

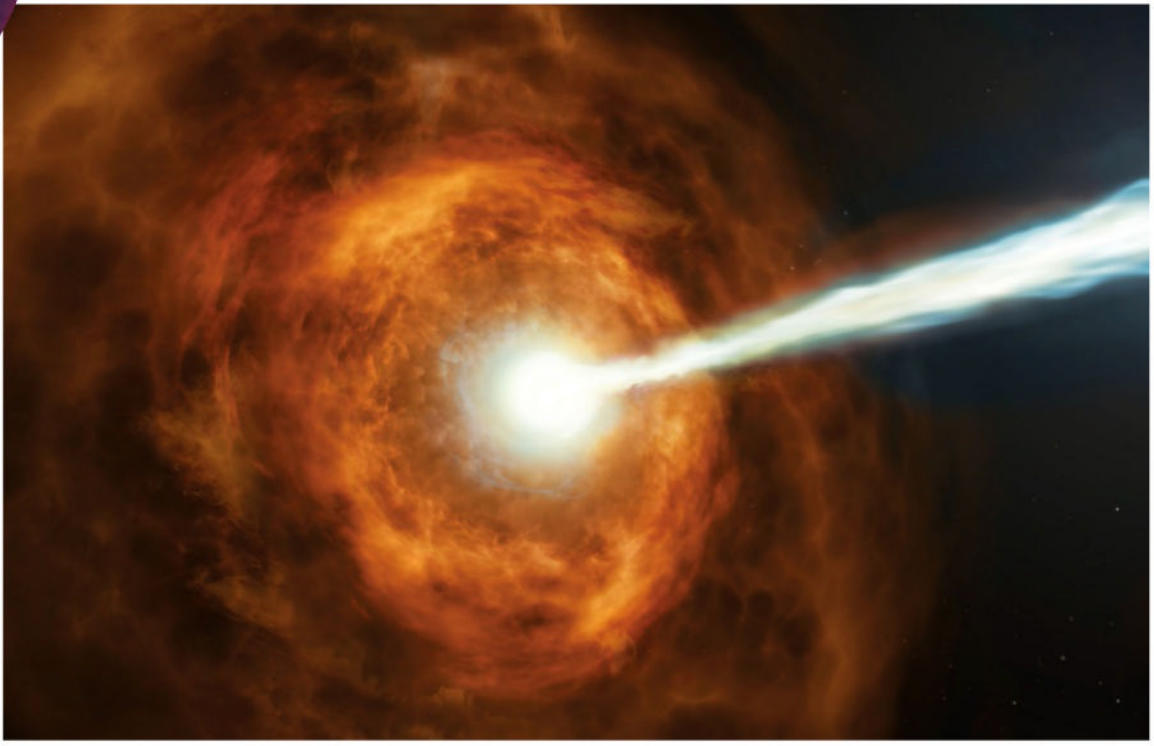
The collapse creates what we see as a black hole, with the event horizon being the shrinking boundary of the object's immense gravitational pull. The Planck star is at the centre, surrounded by the black hole's event horizon.

### They 'bounce' and explode

Once the shrinking event horizon reaches the Planck star at the centre, it bounces back in a massive explosion that could emit detectable gamma rays, appearing as gamma-ray bursts.

### Solving the information paradox

Because we think Planck stars radiate out material when they explode, they would solve the paradox of where information falling into a black hole goes. That information, it seems, would be emitted back into space.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**Above: Gamma-ray bursts might be the result of Planck stars exploding in the early universe**

there could exist a tiny object - a Planck star - that stores all information about infalling material into the black hole. As the black hole evaporates and its gravitational boundary - known as the event horizon - shrinks, it would eventually meet this Planck star, exploding in a violent event and allowing information to then escape into space, supposedly solving the information paradox.

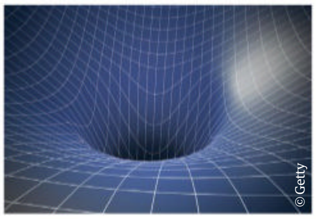
Planck stars would form in much the same way a black hole does. A black hole forms when a very massive star runs out of fuel at the end of its life. With no outward pressure to counteract the incoming force of gravity on the star, it collapses into a singularity and produces a black hole. However, Rovelli and Vidotto argue that that might not be the end of the story. They suggest that a black hole is the process of a massive star exploding like a supernova, with its event horizon gradually shrinking over very long scales.

"The black hole forms in the sense that you have the creation of a horizon," says Vidotto. "But on the inside, the collapse keeps on happening, and at a certain point you have new forces of quantum origin that balance the contraction. So instead of having a contraction that goes on forever and creates a singularity, you have instead these new forces that trigger a new phase that could be an expanding phase. The object that at a certain point corresponds to this maximum contraction is what we call a Planck star."

Eventually this event horizon reaches the middle of the black hole, the singularity, where the remains of the original star have been squashed into a tiny point less than a trillionth of a trillionth of a metre

## Bluffer's guide: loop quantum gravity

How to make two of our competing laws of physics match up with each other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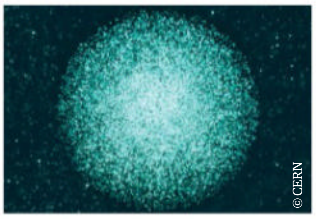
**Laws of physics**

In physics, the Standard Model is a broad theory to explain forces and particles in the universe, while general relativity explains how gravity works.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**Head to head**

The Standard Model and general relativity are not compatible. One can't explain the other. Something else must be going on to make them work together.

© Getty

**The peace maker**

Loop quantum gravity attempts to make quantum mechanics – which governs the very smallest things in the universe – compatible with gravity.

in size, known as the Planck length – the smallest possible length in physics.

Once the event horizon reaches this point, the infalling event horizon bounces out again, and the star unleashes its matter into space. It's an event that should be fairly quick, but the intense gravity of it leads to something called time dilation, and from our point of view, everything is moving slower than it actually is. Thus, when we look at a Planck star, we are seeing the process of a massive star collapsing and rebounding essentially "in slow motion", says Vidotto. From our point of view the entire process takes billions of years, depending on the size of the black hole.

Stefano Liberati from the Scuola Internazionale Superiore di Studi Avanzati (SISSA) in Italy compares the idea to the 2014 film *Interstellar*. In the film the protagonists visit a planet orbiting near a black hole, Gargantua, where time runs more slowly owing to the its immense gravitational pull. "That is basically the time dilation due to the gravitational redshift, which is a phenomenon which we know is there – it's predicted by general relativity," he says. "The idea is that the bounce [of the Planck star] is very fast if you are running the clock on the collapsing star. But seen from outside, there is a huge gravitational time dilation."

A Planck star is a wholly unusual and unstable object, being condensed into the size of an atom. Planck star theory builds upon the idea that black holes have an event horizon and a point of near infinite mass and density at their cores, known as a singularity. The information paradox posits that it is impossible to ever know anything about this singularity, owing to the immense forces involved and the fact that nothing can escape. But if a black hole were actually a Planck star in the process of collapsing and rebounding, it could solve this paradox.

This is similar to one of the proposed theories for the end of the universe, known as the Big Crunch. Our universe is now known to be expanding at an accelerating rate, but scientists once thought the expansion might start to slow, eventually leading the universe to collapse. This would result in the opposite of a Big Bang, known as the Big Crunch or Big Bounce, where all matter in the universe would be condensed to a singularity. Once the

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**Above:** NASA's Fermi Gamma-ray Telescope is used to study gamma rays in the universe

**Below:** Our best chance of finding Planck stars could be looking back to the early universe

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## What we need to know about Planck stars

### How long do they take to explode?

While we think Planck stars are stellar explosions in slow motion, we aren't entirely sure how long they take. We'll need to know that if we ever want to spot one.

### Where are they?

If Planck stars do really exist, it might be possible to spot some of them exploding in our night sky. However, we haven't been able to track any down as of yet.

### Were they in the early universe?

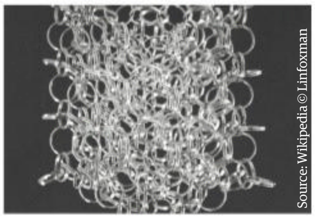
It's possible Planck stars were present in the early universe, in the form of primordial black holes. If we can find some of these, we might be able to find a Planck star.

### Have we seen some already?

Planck stars are thought to release large amounts of gamma rays when they explode. We've already detected many gamma-ray bursts in the universe – could some of those bursts we've found be Planck stars?

### What size are they?

Black holes come in a variety of sizes, but do Planck stars as well? Smaller ones would explode more quickly, so we'd be able to spot them more easily in the universe.



Source: Wikipedia © Linfoxman

### Loop the loop

It works by breaking down space into smaller bits. It suggests space-time is not a continuous sheet, but rather lots of smaller 'loops' joined together.

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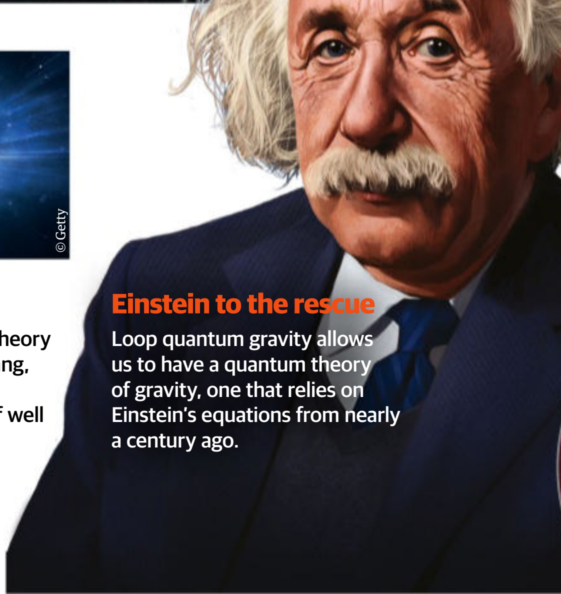
### The Big Bounce

One consequence of this theory is that there was no Big Bang, but instead a Big Bounce – something that lends itself well to Planck star theory.

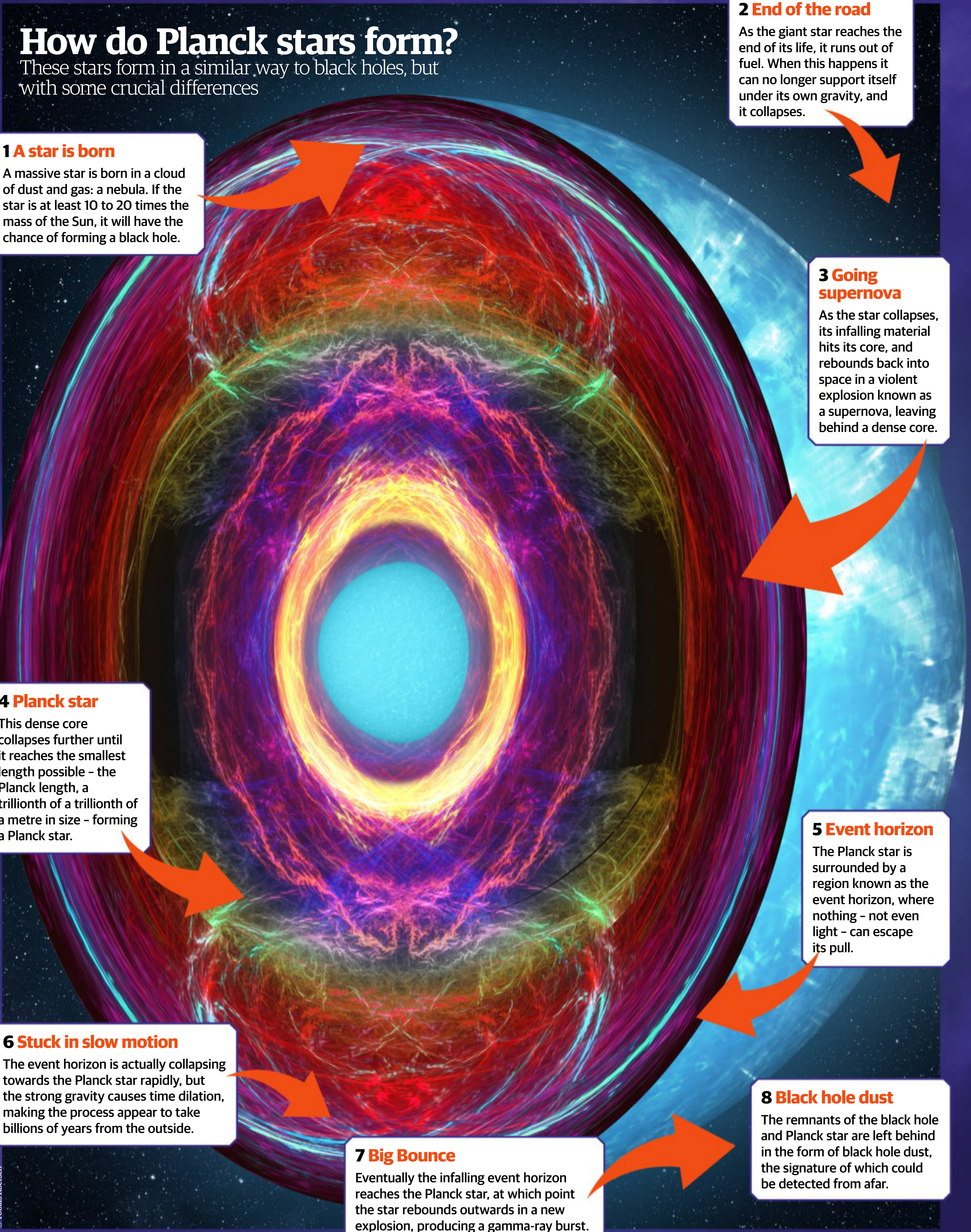


### Einstein to the rescue

Loop quantum gravity allows us to have a quantum theory of gravity, one that relies on Einstein's equations from nearly a century ago.

# How do Planck stars form?

These stars form in a similar way to black holes, but with some crucial differences



**1 A star is born**

A massive star is born in a cloud of dust and gas: a nebula. If the star is at least 10 to 20 times the mass of the Sun, it will have the chance of forming a black hole.

**2 End of the road**

As the giant star reaches the end of its life, it runs out of fuel. When this happens it can no longer support itself under its own gravity, and it collapses.

**3 Going supernova**

As the star collapses, its infalling material hits its core, and rebounds back into space in a violent explosion known as a supernova, leaving behind a dense core.

**4 Planck star**

This dense core collapses further until it reaches the smallest length possible – the Planck length, a trillionth of a trillionth of a metre in size – forming a Planck star.

**5 Event horizon**

The Planck star is surrounded by a region known as the event horizon, where nothing – not even light – can escape its pull.

**6 Stuck in slow motion**

The event horizon is actually collapsing towards the Planck star rapidly, but the strong gravity causes time dilation, making the process appear to take billions of years from the outside.

**7 Big Bounce**

Eventually the infalling event horizon reaches the Planck star, at which point the star rebounds outwards in a new explosion, producing a gamma-ray burst.

**8 Black hole dust**

The remnants of the black hole and Planck star are left behind in the form of black hole dust, the signature of which could be detected from afar.

© Tobias Roetsch

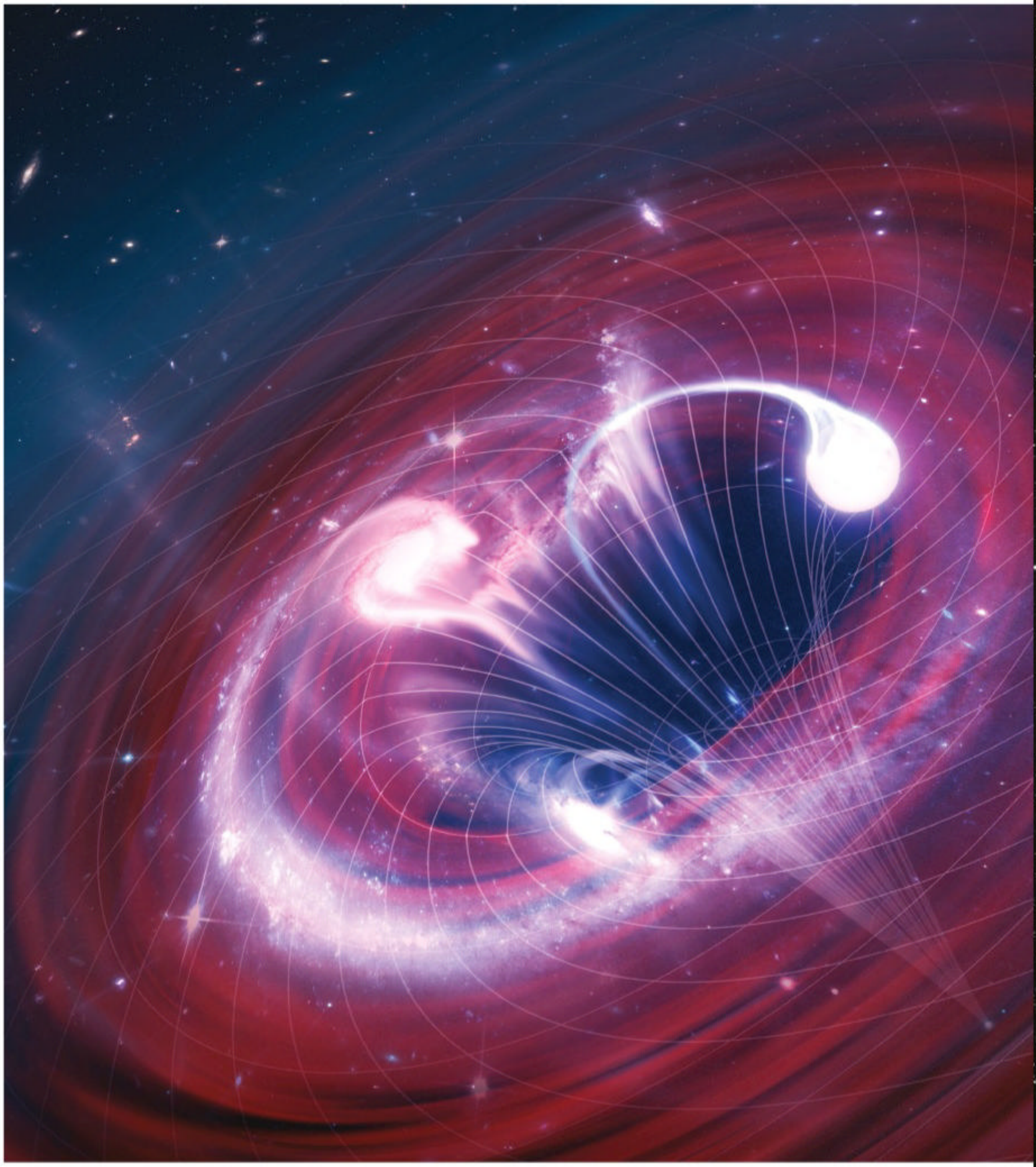
universe reached the so-called Planck length, it would rebound again in a new Big Bang, restarting the universe.

An outstanding issue in physics is that two of our major theories, quantum mechanics and gravity, cannot be reconciled. The former explains things on a very small scale, and the latter on a very large scale, but it's difficult to make them work with each other. One solution is something called loop quantum gravity, the idea that space-time is actually made up of lots of smaller parts, or loops. This theory suggests that the universe is infinite and has always existed, rebounding in numerous Big Bounces in the same way as a Planck star.

"The idea of bouncing comes from ideas that have been developed in the framework of quantum gravity," says Carlos Barceló Serón from the Instituto de Astrofísica de Andalucía in Spain. "What you have is the universe, instead of coming from a singular point, there was a previous universe that was collapsing. And then it reaches this Planck density and then bounces back into our universe. It works very nicely. It has been the inspiration for the [Planck star theory]."

Loop quantum gravity, adds Vidotto, could also be useful in working out the lifetime of Planck stars. "There is an open question that is, 'what is the lifetime of these objects?'" she says. "How long is the life of a Planck star? In order to [answer] that we need a quantum gravity theory to make this computation, and so we are using the tools of loop quantum gravity to do this computation. It's very exciting because applying those tools to such a concrete scenario that may lead to the detection of something is very motivating for people working in quantum gravity."

**Below:** Information must live on somewhere in a black hole to fit within our current understanding



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## Five facts about black holes

Here are five things we know about these unusual objects that play a crucial role in Planck stars

### They come in different sizes

Black holes can range in size from microscopic to supermassive black holes, which are billions of times more massive than our Sun and found in the centre of galaxies.

### They grew really fast

Black holes in the early universe somehow grew really quickly, reaching supermassive status just a billion years after the Big Bang – but scientists aren't sure how.

### We've managed to take an image of one

In April 2019, astronomers from the Event Horizon Telescope (EHT) project revealed they had taken the first image of a black hole, found in the nearby M87 galaxy.

### Despite the name, they can be really bright

Some supermassive black holes are surrounded by swirling discs of superheated material, known as a quasar, which can be easily spotted in telescopes, although the black hole remains hidden.

### There's a missing class of black holes

Astronomers believe the universe might be abundant in a medium-sized type of black hole, called an intermediate-mass black hole. However, we've struggled to find many of them so far.

A black hole's gravity can be so strong that light is forced into an orbital path, creating a photon sphere

© Nicholas Forder

While the Big Bounce theory is now mostly superseded by the heat death theory of the universe – that the universe will continue expanding at an accelerating rate until atoms themselves are torn apart – it does lend itself well to Planck star theory. "The idea is that inside a black hole some bounce should happen," says Vidotto. "What was novel in our approach was we started thinking about what would happen if the bounce phase doesn't go into some strange new universe, but is just a new phase that happened in the future of the black hole."

Vidotto says the idea is similar to that of a 'white hole' – essentially the opposite of a black hole, where everything escapes rather than being trapped. "You have this expanding phase like an explosion," she says. And this means such an event could be possible to see, if a black hole had progressed to this point in its life. "This is something that is observable, and this opens up new possibilities for investigating black holes," she adds, noting there may be detectable remains of this event. "We don't expect the explosion to define the end of the black hole. We expect it to have a new remnant phase that's like black hole dust."

The idea that black holes might evaporate in some way was proposed by the late Stephen Hawking, who said that black holes might be able to leak information in the form of Hawking radiation, providing a potential solution to the information paradox. Under Hawking's proposal, the black hole would gradually evaporate, leaking more and more Hawking radiation until it disappeared completely. But the Planck star theory takes this even further, suggesting it is not just Hawking radiation that escapes, but essentially everything from the Planck star when its bounce phase is over.

Serón notes that there are some issues with the theory, however, notably that this process is expected to take many billions of years, making it hard to test. "The problem with these proposals is that theoretically they are very nice," he says. "The thing is that they're very difficult to prove in real scenarios. The only chance is that some of these objects have been evaporating for a long time. They were formed with small masses at the beginning of the universe, and now they are in the last stages of evaporation. And they could lead to some of the explosions that you see in the sky."

That's something Vidotto is interested in. It might be that some of these objects, if they truly exist, were present in the early universe. Thus, enough time may have passed now that they could have already exploded, letting us see the after-effects of what happened. "There seems to be a convergence in the astrophysics community about the possibility of having primordial black holes," she says. "[These] are black holes that formed in the very early universe. Those may form with a lot of different sizes. We are in particular interested in those that are smaller, so that the timescale for a black hole to form and go through the Planck star phase and explode [is shorter]."

Such events would be in the form of gamma-ray bursts, among the brightest events in the universe. Some of these are thought to be produced when two objects merge together, such as neutron stars and black holes. They may also be produced when supergiant stars go supernova. However, if black holes really do contain Planck stars inside them, then it could be that some gamma-ray bursts are the result of primordial black holes from the early universe exploding.

"The original idea is that they would go for billions and billions of years, so the idea is you could see today Planck stars exploding that were formed in the early universe [like a supernova]," says Liberati. "[They] could be bouncing now. And then we would be able to see the signal now from these kinds of explosions."

Nonetheless, the idea of Planck stars remains somewhat controversial. For one, it is somewhat difficult to prove they exist; peering into the early universe to spot primordial black holes is difficult. Although some have been theorised, actually finding them is much harder in practice, and thus seeing any events associated with a Planck star is also incredibly difficult. And the idea of a Big Bounce for the universe also seems to go against many of our observations of the universe, which actually suggest that it is expanding at an accelerating rate.

Vidotto, however, is hopeful that Planck stars really do exist, and continuing efforts are being made both to work on the theory of their existence, and to perform observations to look for them. She says researchers are developing new loop quantum gravity tools that could be useful in predicting some of the properties of Planck stars, and perhaps tell us what we might expect to see if we managed to spot one exploding.

"This idea puts together some old ideas, but in a really new way that opens up a new direction of research," she says. "The idea that inside a black hole there is not a singularity, there is a Planck star – this is something I'm pretty convinced of."

> "Inside a black hole there is not a singularity, there is a Planck star… I'm pretty convinced" **Francesca Vidotto**

MYSTERIES OF THE UNIVERSE

# WHERE DO BLACK HOLES LEAD?

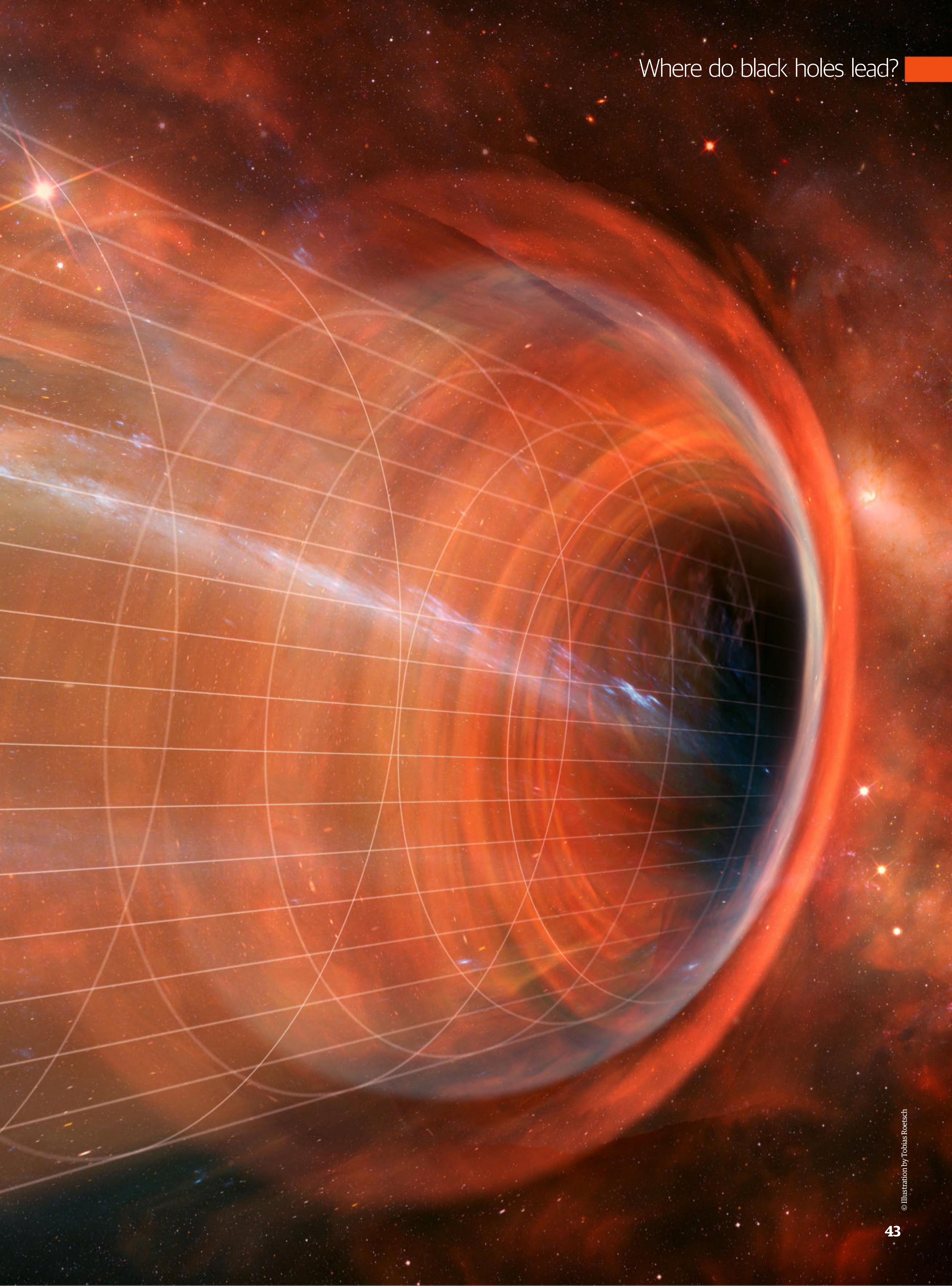
If you could journey through the cosmos' most monstrous objects, what tales – if any – would you be able to tell?

**Reported by David Crookes**

So there you are, about to leap into a black hole. What could possibly await should – against all odds – you somehow survive? Where would you end up and what tantalising tales would you be able to regale to friends and family if you managed to clamour your way back?

The simple answer to all of these questions is, as Professor Richard Massey explains, "Who knows?" As Royal Society research fellow at the Institute for Computational Cosmology at Durham University, he is fully aware that the mysteries of black holes run deep. "Falling through an event horizon is literally passing beyond the veil – once someone falls past it, nobody could ever send a message back," he says. "They'd be ripped to pieces by the enormous gravity, so I doubt anyone falling through would get anywhere."

If that sounds like a disappointing – and painful – answer, then it is to be expected. Ever since Albert Einstein's general theory of relativity was considered to have predicted black holes by linking



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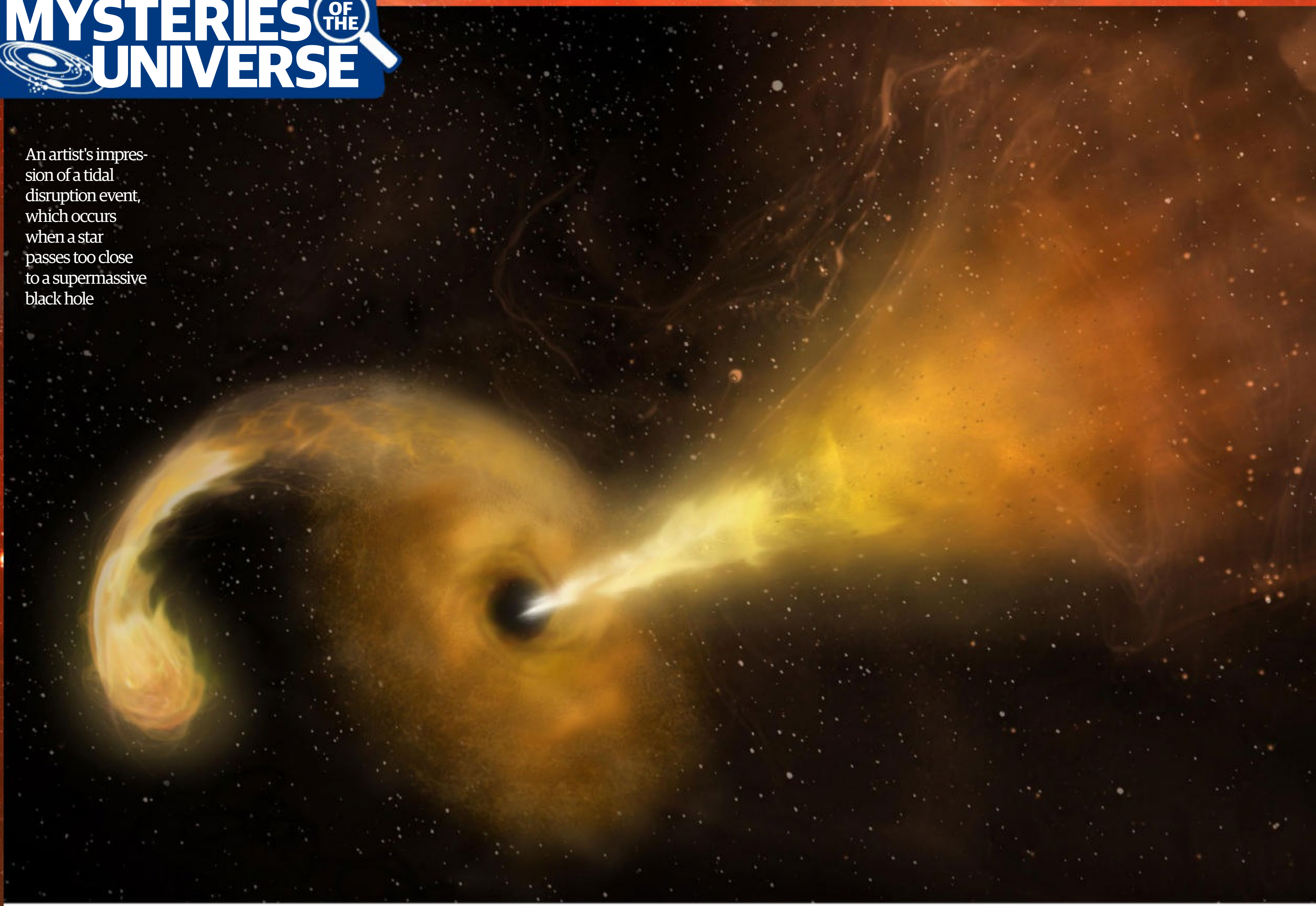


An artist's impression of a tidal disruption event, which occurs when a star passes too close to a supermassive black hole

space-time with the action of gravity, it has been known that black holes result from the death of a massive star leaving behind a small, dense remnant core. Assuming this core has more than roughly three times the mass of the Sun, gravity would overwhelm to such a degree that it would fall in on itself into a single point, or singularity, understood to be the black hole's infinitely dense core.

"Black holes should be redefined as metastable bound states of the gravitational field" **Stephen Hawking**

The resulting uninhabitable black hole would have such a powerful gravitational pull that not even light could avoid it. So should you then find yourself at the event horizon - the point at which light and matter can only pass inward, as proposed by the German astronomer Karl Schwarzschild - there is no escape. As Massey says, tidal forces would reduce your body into strands of atoms - or 'spaghettification', as it is also known - and the object would eventually end up crushed at the singularity. The idea that you could pop out somewhere - perhaps at the other side - seems utterly fantastical.

Or is it? Over the years scientists have looked into the possibility that black holes could be wormholes to other galaxies. They may even be, as some have suggested, a path to another universe.

Such an idea has been floating around for some time: Einstein teamed up with Nathan Rosen to theorise bridges that connect two different points in space-time in 1935. But it gained some fresh ground in the 1980s when physicist Kip Thorne - one of the world's leading experts on the astrophysical implications of Einstein's general theory of relativity - raised a discussion about whether objects could physically travel through them.

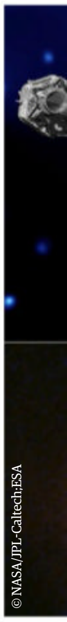
"Reading Kip Thorne's popular book about wormholes is what first got me excited about physics as a child," says Massey. "But the only details I can remember are that stable, traversable wormholes are very unlikely to exist. To stop a wormhole instantly collapsing into an ordinary black hole, you need a ring of some weird matter that has less than zero mass and therefore repulsive gravity. And even if this type of matter happens to be manufacturable, shaping it into a ring then needs either a huge amount of luck straight after the Big Bang, or some very advanced aliens."

Indeed, Thorne, who lent his expert advice to the production team for the Hollywood movie *Interstellar*, wrote: "We see no objects in our universe that could become wormholes as they age," in his 2014 book *The Science of Interstellar*. He also told our sister publication, space.com, that journeys through these theoretical tunnels would most likely remain science fiction, and there is certainly no firm evidence that a black hole could allow for such a passage.

We can't get up close to see for ourselves. Why, we can't even take photographs of anything that takes place inside a black hole - if light cannot escape their huge gravity, then nothing can be snapped by a camera. As it stands, theory suggests that anything which does go beyond the event horizon is simply added to the black hole and, what's more, because time distorts close to this boundary, this will appear to take place incredibly slowly, so answers won't be quickly forthcoming - to a distant observer, clocks that are near a black hole would appear to tick less fast than one further away.

"I think the standard story is that they lead to the end of time," says Douglas Finkbeiner, professor of astronomy and physics at Harvard University. "An observer far away will not see their astronaut friend fall into the black hole. They'll just get redder and fainter as they approach the event horizon [as a result of gravitational red shift]. But the friend falls right in, to a place beyond 'forever'. Whatever that means."

Certainly, if black holes do lead to another part of a galaxy or another universe, there would need to be something opposite to them on the other



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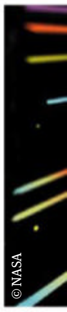

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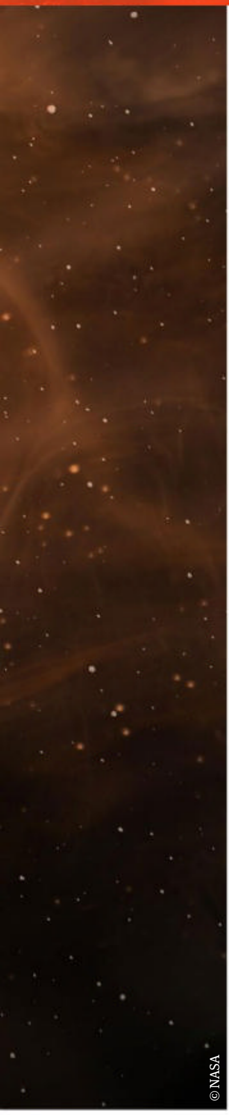

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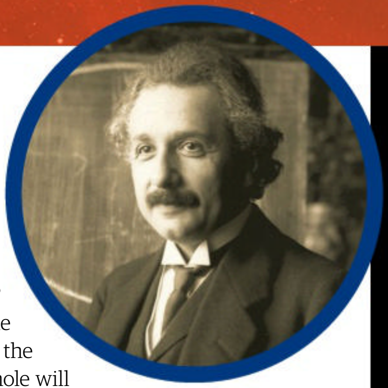


side. Could this be a white hole – a theory put forward by Russian cosmologist Igor Novikov in 1964? Novikov proposed that a black hole links to a white hole that exists in the past. Unlike a black hole, a white hole will allow light and matter to leave. Again, unlike black holes, light and matter will not be able to enter.

White holes were said to be evident in mysterious invisible radio sources, first spotted by Maarten Schmidt, a Caltech astronomer working at Palomar Observatory. In 1963 he discovered a distant object some 2 billion light years away that was shining so bright that it was actually greater than the Milky Way in its entirety. The object – 3C 273 – was subsequently referred to as a quasi-stellar radio source, or quasar, and there were later suggestions that quasars were, in fact, openings of these proposed white holes.

Very few scientists today believe white holes are quasars. But a potential connection between black and white holes is still being explored. Carlo Rovelli and Hal M Haggard wrote a paper in 2014 which claimed to “show that there is a classic metric satisfying the Einstein equations outside a finite space-time region where matter collapses into a black hole and then emerges from a while hole”. In other words, all of the material black holes have swallowed could be spewed out, and black holes may become white holes when they die.

Far from destroying the information that it absorbs, the collapse of a black hole would be

**Above:** Albert Einstein's general theory of relativity provides the foundation for the current understanding of black holes

**Bottom left:** NASA's Nuclear Spectroscopic Telescope Array (NuSTAR) is conducting a deep survey for black holes

**Bottom right:** Could wormholes formed from black holes – if they exist – allow travel from one part of the galaxy to another?

# The theories

## Where do scientists believe information plunged into a black hole may end up?

### General relativity

It still holds that our best theory of gravity is the one that Einstein came up with more than 100 years ago. It predicts locations where space-time ends and gravity becomes infinite – the point of singularity. Gravitational forces beyond the event horizon cause spaghettification and eventual crushing. Information is lost forever.

### Loop quantum gravity

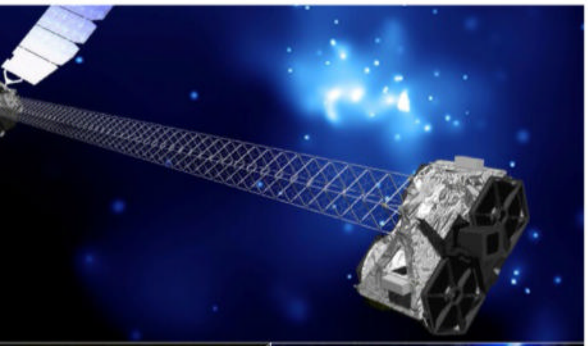
LQG merges quantum mechanics and general relativity and seeks to show that singularities cannot exist. Instead, the theory predicts that a funnel exists that leads to another branch of the space-time, perhaps creating an entry point to another universe. It means information is not lost and merely ends up elsewhere.

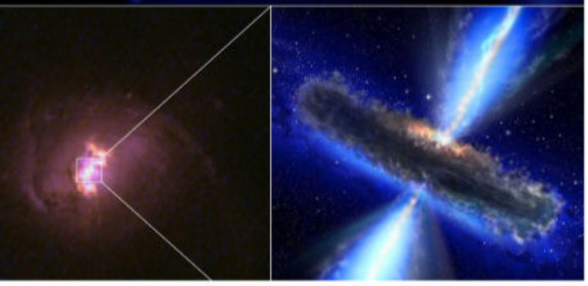
### Black holes disappear

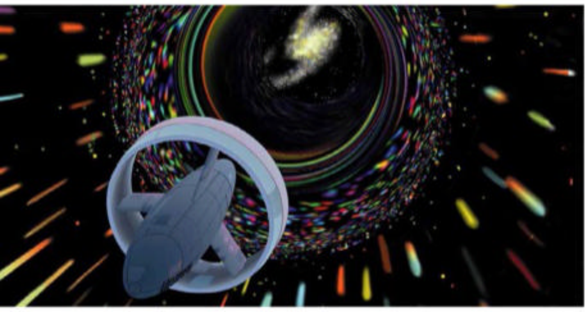
Stephen Hawking suggested in 1974 that black holes eventually evaporate. They emit particles – or Hawking radiation – which eventually causes enough energy and mass to be lost. Physicists have tested this theory in a lab using Bose-Einstein concentrate made of gas and particles cooled to near absolute zero. It found what was captured would trickle away.

### No-hair theorem debunked

Hawking's theory still suggested that most of the information that fell into a black hole would be erased: only details of the mass, charge and angular momentum would survive. But string theory suggested information cannot be lost. Hawking and other scientists found black holes have 'soft hair' – low-energy quantum excitations which release information when black holes evaporate.







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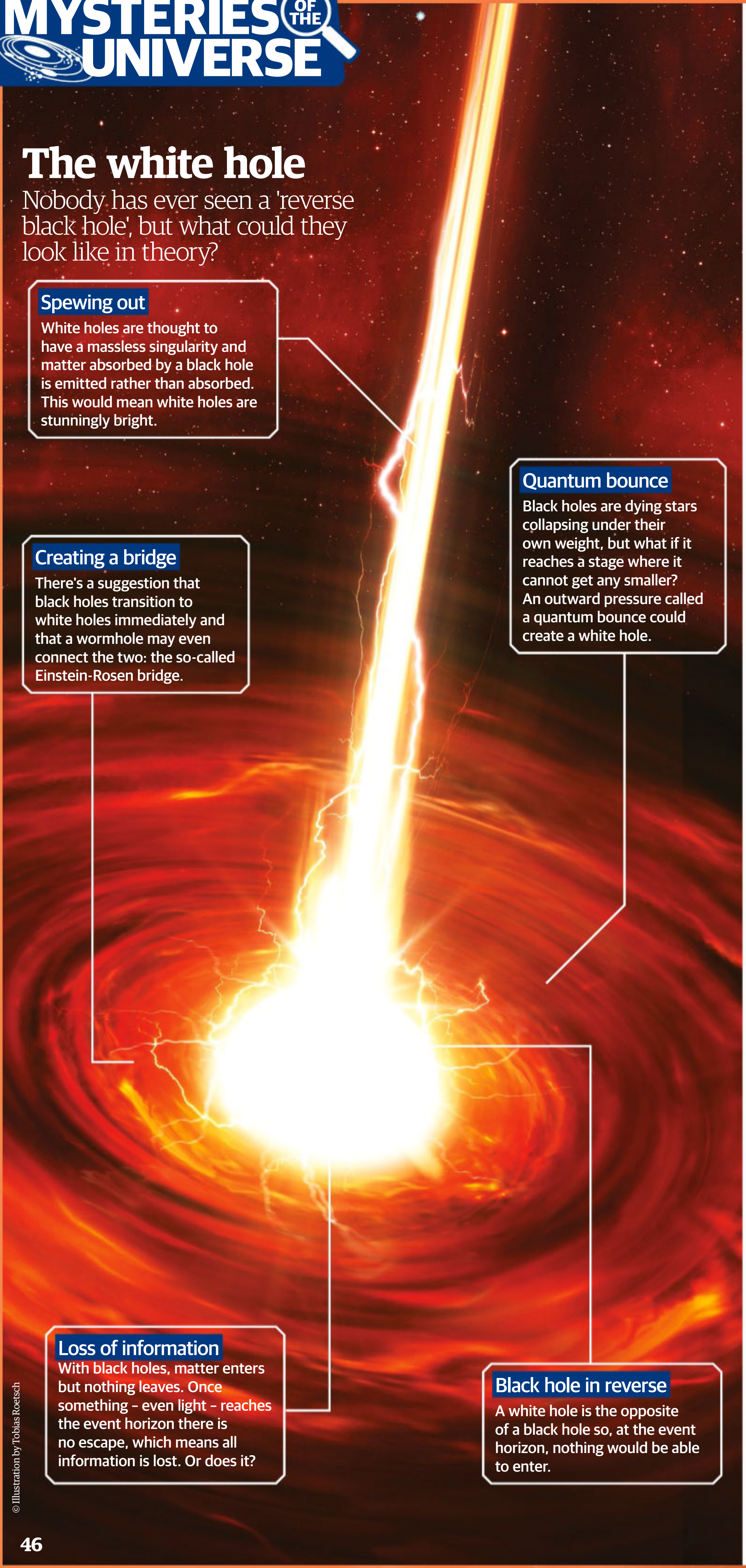
# The white hole

Nobody has ever seen a 'reverse black hole', but what could they look like in theory?



**Spewing out**

White holes are thought to have a massless singularity and matter absorbed by a black hole is emitted rather than absorbed. This would mean white holes are stunningly bright.

**Creating a bridge**

There's a suggestion that black holes transition to white holes immediately and that a wormhole may even connect the two: the so-called Einstein-Rosen bridge.

**Quantum bounce**

Black holes are dying stars collapsing under their own weight, but what if it reaches a stage where it cannot get any smaller? An outward pressure called a quantum bounce could create a white hole.

**Loss of information**

With black holes, matter enters but nothing leaves. Once something – even light – reaches the event horizon there is no escape, which means all information is lost. Or does it?

**Black hole in reverse**

A white hole is the opposite of a black hole so, at the event horizon, nothing would be able to enter.

© Illustration by Tobias Roetsch

halted. It would instead experience a quantum bounce, allowing information to escape. Should this be the case, it would shed some light on a proposal by former Cambridge University cosmologist and theoretical physicist Stephen Hawking who, in the 1970s, explored the possibility that black holes emit particles and radiation – thermal heat – as a result of quantum fluctuations.

"Hawking said a black hole doesn't last forever," explains Finkbeiner. Indeed, the acclaimed scientist calculated that the radiation would cause a black hole to lose energy, shrink and disappear in a paper published in 1976, called *The Breakdown of Predictability in Gravitational Collapse*. Given his claims that the radiation emitted would be random and contain no information about what had fallen in, the black hole, upon its explosion, would mean masses of information being forever erased.

This put it at odds with quantum theory, which says information can't be destroyed. Physics states information just becomes more difficult to find because, should it become lost, it becomes impossible to know the past or the future. Hawking's idea led to the 'black hole information paradox' and it has long puzzled scientists. Some have said Hawking was simply wrong, and the man himself even declared he had made an error during a scientific conference in Dublin in 2004.

So does that back the concept of black holes emitting preserved information and throwing it back out via a white hole? Maybe. Jorge Pullin at Louisiana State University and Rodolfo Gambini at the University of the Republic in Montevideo, Uruguay, applied loop quantum gravity to a black hole in 2013 and found that gravity increased towards the core but reduced and plonked whatever was entering into another region of the universe, lending extra credence to the idea of black holes serving as a portal. In this study singularity doesn't exist, and so it doesn't form an impenetrable barrier that ends up crushing whatever it encounters. It also means that information doesn't disappear.

> "Falling through an event horizon is passing beyond the veil -nobody could send a message back" **Richard Massey**

Yet physicists Ahmed Almheiri, Donald Marolf, Joseph Polchinski and James Sully still believed Hawking could have been on to something. They worked on a theory that became known as the AMPS firewall, or the black hole firewall hypothesis. By their calculations, quantum mechanics could feasibly turn the event horizon into a giant wall of fire and that anything coming into contact would burn in an instant. In that sense, black holes lead nowhere because nothing could ever get inside.

This, however, violates Einstein's general theory of relativity. Someone crossing the event horizon shouldn't actually feel any great hardship because an object would be in free fall and, based on the equivalence principle, that object - or person - would not feel the extreme effects of gravity.

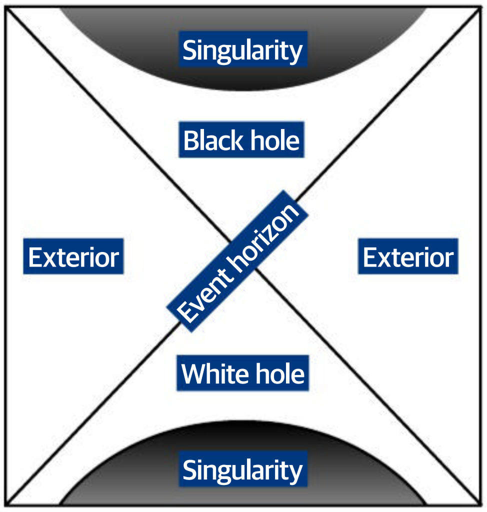
It should follow the laws of physics present elsewhere in the universe, but even if it didn't go against Einstein's principle, it would still undermine quantum field theory or suggest information can actually be lost. Scientists were on the hunt for a viable explanation.

Step forward Hawking once more. In 2014 he wrote a paper called *Information and Weather Forecasting for Black Holes* in which he eschewed the existence of an event horizon - meaning there is nothing there to burn - saying gravitational collapse would produce an 'apparent horizon' instead.

This horizon would suspend light rays trying to move away from the core of the black hole, and would persist for a 'period of time'. In his rethinking apparent horizons temporarily retain matter and energy before dissolving and releasing them later down the line. The explanation best fits with quantum theory - which says information can't be destroyed - and, if it was ever proven, it suggests that anything could escape from a black hole.

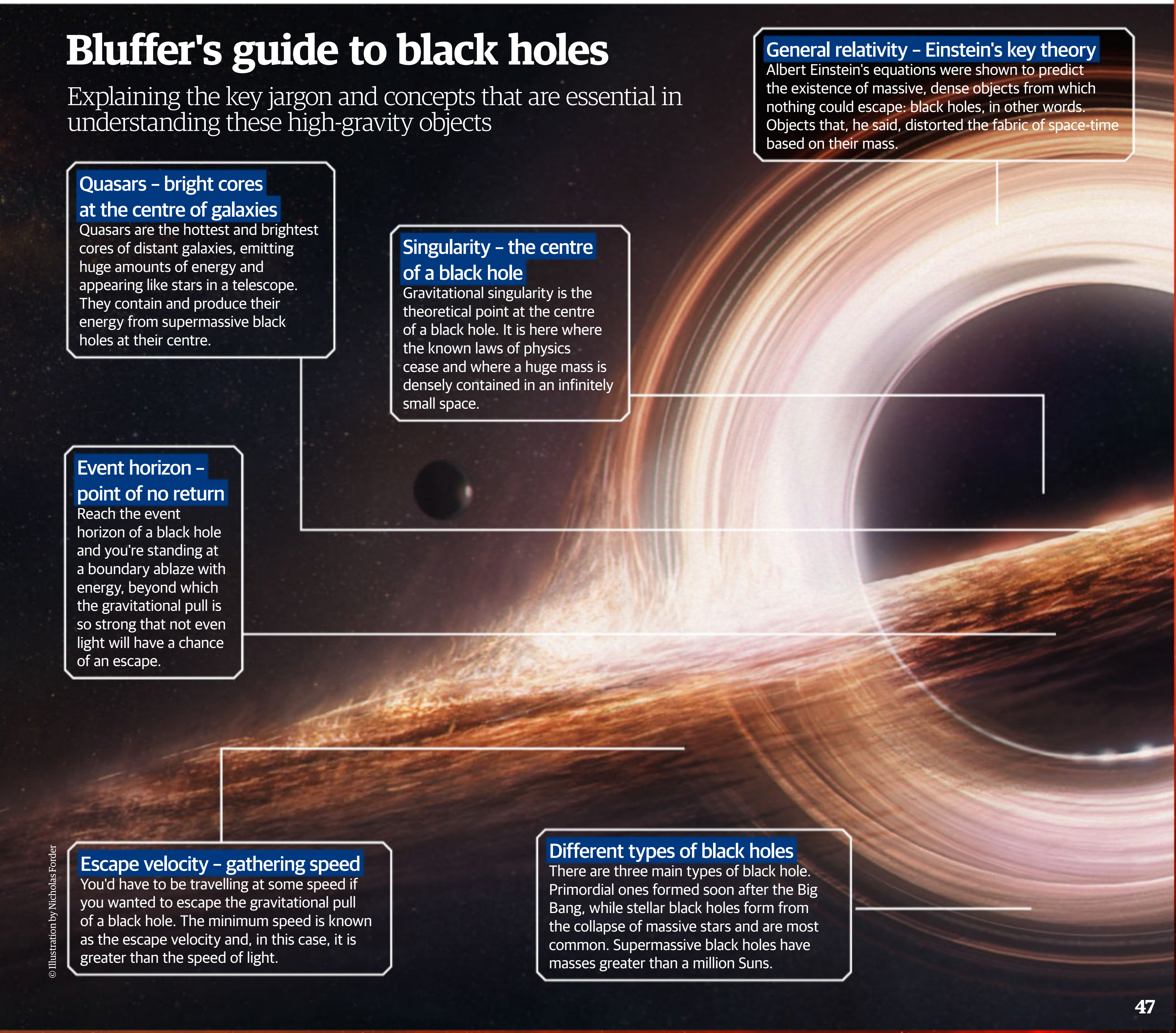
Hawking went as far as saying black holes may not even exist. "Black holes should be redefined as metastable bound states of the gravitational field," he wrote. There would be no singularity, and while the apparent field would move inwards due to gravity, it would never reach the centre and be consolidated within a dense mass.

And yet anything that is emitted will not be in the form of the information swallowed. It would not



# Bluffer's guide to black holes

Explaining the key jargon and concepts that are essential in understanding these high-gravity objects



### General relativity – Einstein's key theory

Albert Einstein's equations were shown to predict the existence of massive, dense objects from which nothing could escape: black holes, in other words. Objects that, he said, distorted the fabric of space-time based on their mass.

### Quasars – bright cores at the centre of galaxies

Quasars are the hottest and brightest cores of distant galaxies, emitting huge amounts of energy and appearing like stars in a telescope. They contain and produce their energy from supermassive black holes at their centre.

### Singularity – the centre of a black hole

Gravitational singularity is the theoretical point at the centre of a black hole. It is here where the known laws of physics cease and where a huge mass is densely contained in an infinitely small space.

### Event horizon – point of no return

Reach the event horizon of a black hole and you're standing at a boundary ablaze with energy, beyond which the gravitational pull is so strong that not even light will have a chance of an escape.

### Escape velocity – gathering speed

You'd have to be travelling at some speed if you wanted to escape the gravitational pull of a black hole. The minimum speed is known as the escape velocity and, in this case, it is greater than the speed of light.

### Different types of black holes

There are three main types of black hole. Primordial ones formed soon after the Big Bang, while stellar black holes form from the collapse of massive stars and are most common. Supermassive black holes have masses greater than a million Suns.

© Illustration by Nicholas Forder

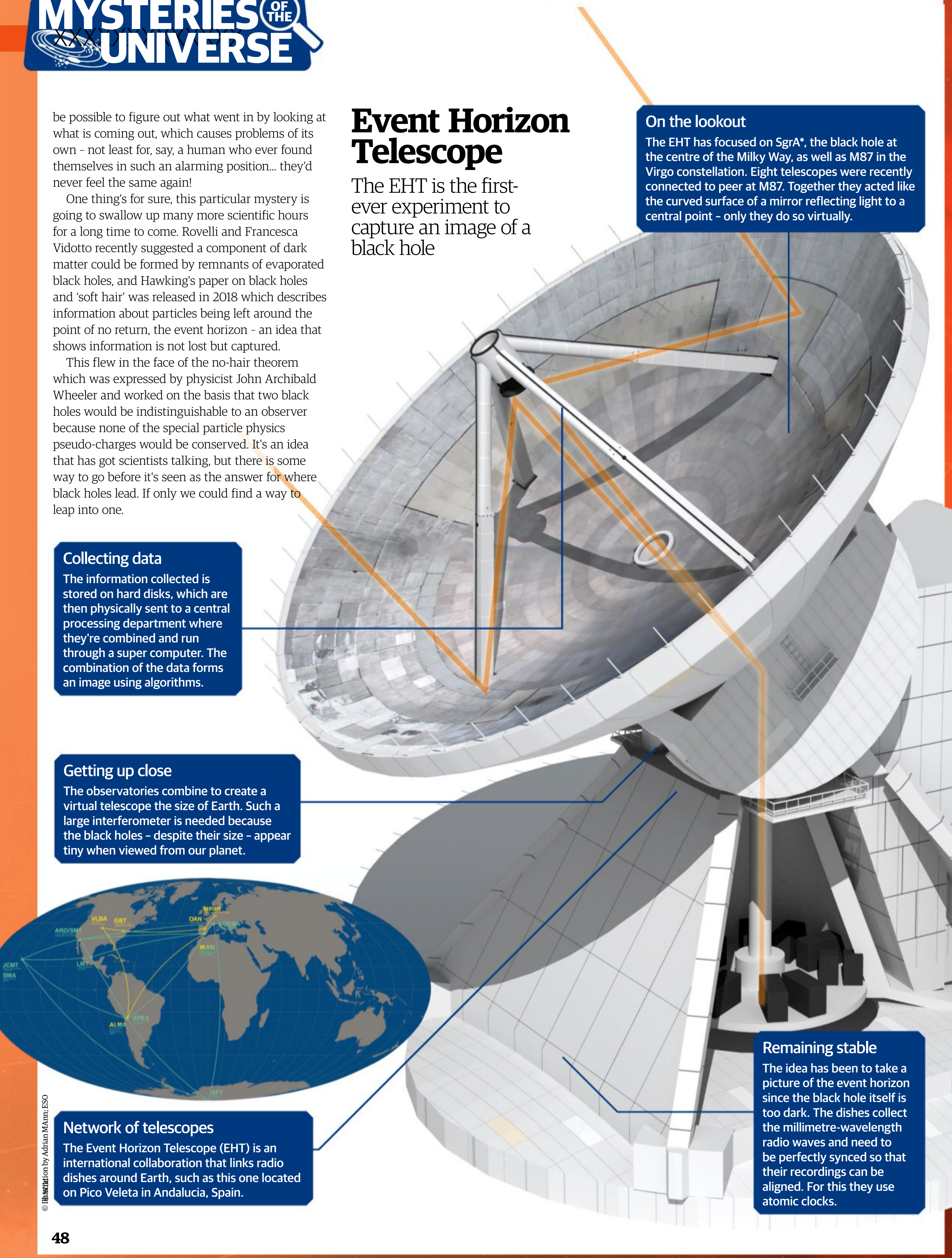
be possible to figure out what went in by looking at what is coming out, which causes problems of its own – not least for, say, a human who ever found themselves in such an alarming position… they'd never feel the same again!

One thing's for sure, this particular mystery is going to swallow up many more scientific hours for a long time to come. Rovelli and Francesca Vidotto recently suggested a component of dark matter could be formed by remnants of evaporated black holes, and Hawking's paper on black holes and 'soft hair' was released in 2018 which describes information about particles being left around the point of no return, the event horizon – an idea that shows information is not lost but captured.

This flew in the face of the no-hair theorem which was expressed by physicist John Archibald Wheeler and worked on the basis that two black holes would be indistinguishable to an observer because none of the special particle physics pseudo-charges would be conserved. It's an idea that has got scientists talking, but there is some way to go before it's seen as the answer for where black holes lead. If only we could find a way to leap into one.

## Event Horizon Telescope

The EHT is the first-ever experiment to capture an image of a black hole



### On the lookout

The EHT has focused on SgrA*, the black hole at the centre of the Milky Way, as well as M87 in the Virgo constellation. Eight telescopes were recently connected to peer at M87. Together they acted like the curved surface of a mirror reflecting light to a central point – only they do so virtually.

### Collecting data

The information collected is stored on hard disks, which are then physically sent to a central processing department where they're combined and run through a super computer. The combination of the data forms an image using algorithms.

### Getting up close

The observatories combine to create a virtual telescope the size of Earth. Such a large interferometer is needed because the black holes – despite their size – appear tiny when viewed from our planet.

### Network of telescopes

The Event Horizon Telescope (EHT) is an international collaboration that links radio dishes around Earth, such as this one located on Pico Veleta in Andalucia, Spain.

### Remaining stable

The idea has been to take a picture of the event horizon since the black hole itself is too dark. The dishes collect the millimetre-wavelength radio waves and need to be perfectly synced so that their recordings can be aligned. For this they use atomic clocks.

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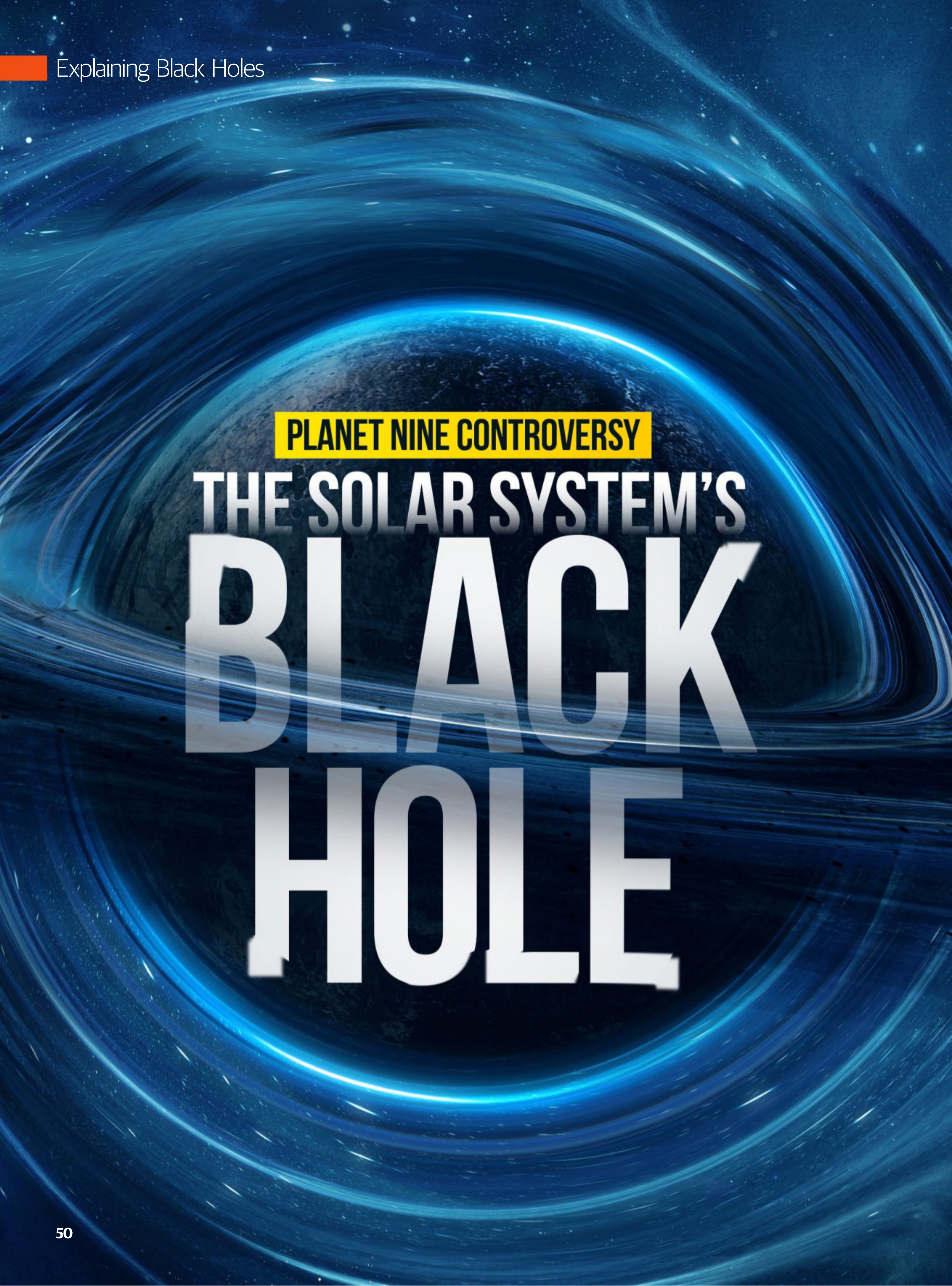


**PLANET NINE CONTROVERSY**

# THE SOLAR SYSTEM'S BLACK HOLE

© Tobias Roetsch

# As the hunt for a mysterious world at our solar neighbourhood's edge steps up, something more exotic might also fit the bill

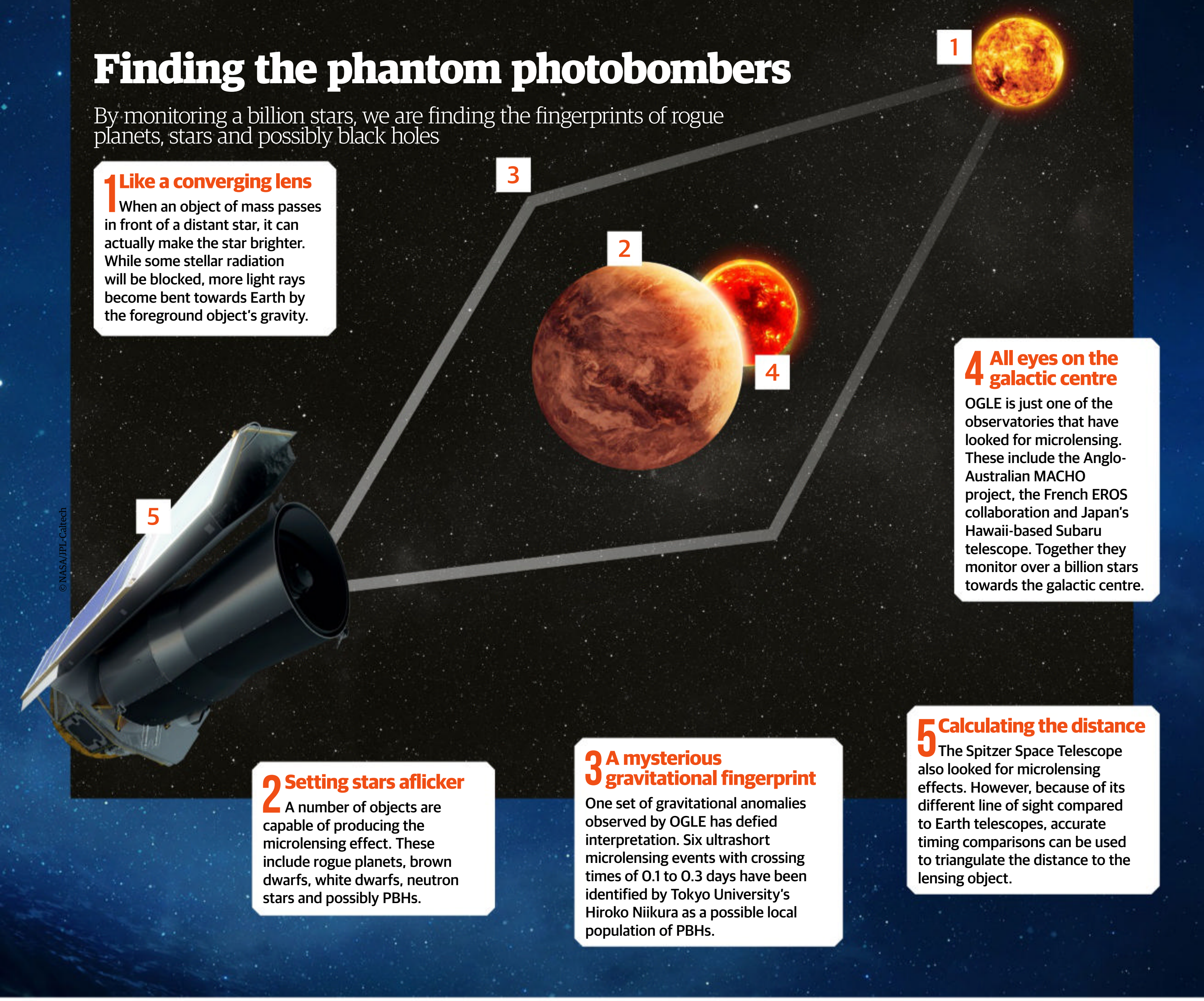
Reported by James Romero

In 2016 Mike Brown, the astronomer who removed Pluto's status as a planet, added a hypothetical one back in to explain strange orbits in the outer Solar System. In 2015 the Vera C. Rubin Observatory will map those celestial backwaters to help find Brown's Planet Nine. But what if this target can't be seen?

It's a possibility that hit the headlines when Planet Nine was replaced, at least in excited media headlines, by an ancient black hole. Brown himself addressed the possibility, writing on Twitter: "P9 could definitely be a black hole, as long as it is the right mass. In fact, it could also be a six-Earth-mass hamburger." So is a black hole lurking in the outer Solar System a statistical possibility worth considering? Or a whopper of a stab in the dark?

# Finding the phantom photobombers

By monitoring a billion stars, we are finding the fingerprints of rogue planets, stars and possibly black holes



### 1 Like a converging lens

When an object of mass passes in front of a distant star, it can actually make the star brighter. While some stellar radiation will be blocked, more light rays become bent towards Earth by the foreground object's gravity.

### 4 All eyes on the galactic centre

OGLE is just one of the observatories that have looked for microlensing. These include the Anglo-Australian MACHO project, the French EROS collaboration and Japan's Hawaii-based Subaru telescope. Together they monitor over a billion stars towards the galactic centre.

### 2 Setting stars aflicker

A number of objects are capable of producing the microlensing effect. These include rogue planets, brown dwarfs, white dwarfs, neutron stars and possibly PBHs.

### 3 A mysterious gravitational fingerprint

One set of gravitational anomalies observed by OGLE has defied interpretation. Six ultrashort microlensing events with crossing times of 0.1 to 0.3 days have been identified by Tokyo University's Hiroko Niikura as a possible local population of PBHs.

### 5 Calculating the distance

The Spitzer Space Telescope also looked for microlensing effects. However, because of its different line of sight compared to Earth telescopes, accurate timing comparisons can be used to triangulate the distance to the lensing object.

Answers are out there among trans-Neptunian objects (TNOs). Ancient debris left over from planet formation, the TNOs were swept up by a young, migrating Neptune and dumped far from the Sun in the Kuiper Belt. The ice giant's hold on this ring of rubble continues today, though its influence has changed. Once the source of gravitational chaos, Neptune now brings order to the Kuiper Belt. Any resident knocked out of the orbital plane is brought into line. "TNOs are really interesting because they explore the outer reaches of the Solar System, but they're partially driven by Neptune, which gives them a little kick," says Jakub Scholtz of Durham University. "These kicks randomise them in such a way that they should look pretty uniform."

It was the lack of uniformity that made Brown and his California Institute of Technology (Caltech) colleague Konstantin Batygin's discovery so intriguing. Six TNOs with similarly tilted orbits were all found pointing in a similar direction. Worldwide headlines followed when the culprit was identified as a five to ten Earth-mass planet. The theory raised questions, primarily about what a large planet was doing out there. Observations of other planetary systems have shown building materials that far out in short supply, ruling out in-situ formation. Was Planet Nine another reject from the inner Solar System, or a captured interstellar wanderer?

Scholtz doubts the ejected planet scenario, however, as a single gravitational kick simply elongates a planet's orbit. Its closest approach would still stay roughly the same unless you can account for a series of kicks, which is significantly less likely. The other major question was more obvious. If Planet Nine was a victim of cosmic piracy, where is the stolen bounty?

This was always going to be a challenging hunt. Planet Nine is thought to be several times the size of Earth due to the observed influence, but it's way out there, at least ten-times further than Neptune. Leading the search in recent years has been the Dark Energy Survey, which maps the Kuiper Belt looking for unexplained gravitational influence. Meanwhile NASA's Backyard Worlds project posts images from the Wide-field Infrared Survey Explorer (WISE) for the public to search themselves.

Neither have found their prime target, which is why many hopes are pinned on the Vera C. Rubin Observatory. Coming online in 2025, it aims to characterise around 40,000 TNOs and scattered-disc objects. "If Planet Nine is a conventional planet, I think it is expected to be discovered by the Vera Rubin Observatory," says Ed Witten, a theoretical physicist at the Institute for Advanced Study.

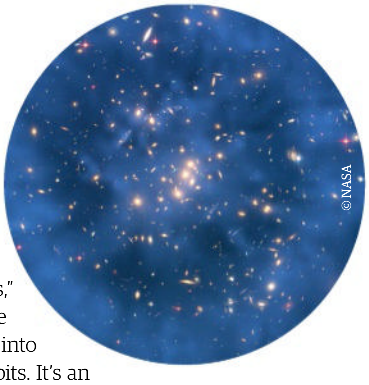
But perhaps Planet Nine isn't a planet at all. As Brown acknowledged, all we know about it is its influence on TNOs. Everything else is inferred. And while there was no reason to doubt Brown and Batygin's original suspect, a challenger emerged when Scholtz and James Unwin, assistant professor at the University of Illinois at Chicago, came across something interesting in the Chilean Andes. There the Optical Gravitational Lensing Experiment (OGLE) monitors a billion stars towards the galactic centre, looking for shadowy brown dwarfs and free-floating planets passing across the starfield.

The resulting gravitational 'microlensing' events give clues about their mysterious photobombers. However, one microlensing signature proved difficult to attribute. Ultrashort occultation events lasting just a few hours kept appearing. The OGLE team's conclusion was a local population of free-floating planets. But six nearby rogue worlds seemed a lot given the average number of planets produced per star across the galaxy.

In January 2019, Tokyo University's Hiroko Niikura proposed a radically different culprit: a community of nearby primordial black holes (PBHs). These were proposed by Stephen Hawking in the 1970s as a product of the early universe, when all matter was packed together. This meant random patches of slightly elevated density could frequently reach a critical level that trapped them behind gravitational points of no return. The result was huge numbers of low-mass black holes.

For a few decades, PBHs were best known as a potential explanation for dark matter. Mostly because you didn't need to conjure up new particles, and cosmologist's models could produce universes full of them. However, in recent decades OGLE and other microlensing surveys have dashed those hopes by drawing blanks for many critical proposed PBH masses. "There's still some window," says Kathryn Zurek, a dark matter theorist at Caltech. "They could be 10 per cent or 20 per cent of dark matter, but you're not driven to them as a candidate in comparison to 20 or 30 years ago."

> "Planet nine could definitely be a black hole, as long as it is the right mass" **Mike Brown**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While the dark matter mystery remains, Niikura's paper claimed a local PBH population of 0.5 to 20 Earth masses could reproduce OGLE's six ultrashort microlensing events. For Scholtz and Unwin, that familiar mass range immediately caught the eye. "As physicists we're trained to think there are no coincidences," says Scholtz, who wondered if one of Niikura's black holes was lured into the Solar System to warp TNO orbits. It's an intriguing scenario, not least because it replaces our ninth world with something far smaller.

To investigate their idea, Scholtz and Unwin compared capture probabilities for rogue planets and pocket black holes. In a paper posted in September 2019, they took a number for rogue planets passing through our Solar System based on planet production and ejection per star, and one for the population of PBHs predicted by OGLE. They applied these to a 2017 model from Nadav Goulinski at the Israel Institute of Technology that allows you to throw bodies of various mass and velocity at our Solar System to see what sticks.

Goulinski's model highlighted two points: rogue planet capture is rare, but black hole capture is rarer still. While the model suggests a quarter of a kilometre per second as a top-end velocity for

**Above:** For decades, PBHs were best known as a potential explanation for dark matter

**Below:** The OGLE observatory looks for the fingerprints of free-floating planets passing across the starfield

© NASA

## Residents of the outer Solar System

What else lies in this cold region of space?

### Pluto

© NASA

Perhaps the most famous resident of the Belt, Pluto is the largest and most massive member. It is also the most studied, thanks to the New Horizons probe.

### Sedna

© NASA/JPL-Caltech

Sedna has an extreme orbit that ranges from 76 AU to over 900. While Planet Nine doesn't explain Sedna's orbit, it could provide the buffer that kept it from being ejected.

### Haumea

© José Antonio Peñas (SINC)

Though not directly observed, Haumea is thought to be an ellipsoid world. In October 2017, astronomers announced the discovery of a ring system, the first around a trans-Neptunian object.

### Eris

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About the same size as Pluto, this dwarf planet and its small moon Dysnomia orbit three-times farther from the Sun. Its high-eccentricity orbit means it was likely scattered by Neptune.

### 2012 VP$_{113}$

© NASA/JPL-Caltech

A minor planet with the farthest closest approach to the Sun in the Solar System, this extreme TNO's orbit was interpreted as evidence of Planet Nine.

### Makemake

Orbiting at a highly inclined 29 degrees to the plane of the Solar System, Makemake's orbit lies far enough from Neptune to remain stable and free from perturbation from the ice giant.

© ESO

capture, rogue planets travel at the velocity of their parent stars, at around 40 kilometres (24.9 miles) per second. PBHs are thought to move at the velocity of cold, collisionless dark matter, expected to be several times faster again. But cosmic piracy is a numbers game, and while rogue planets are more speed matched to our Solar System, their lower frequency seems to even things up.

"I don't want to use the word miraculous, but surprisingly it almost cancels out," says Scholtz. "If you were willing to think about Planet Nine as a captured rogue planet, then given the OGLE result, you should consider thinking about it as a captured black hole."

Not everyone agrees. Zeeve Rogoszinski is a planetary dynamics researcher at the University of Maryland. He questions Scholtz's dismissal of planetary ejection to account for Planet Nine's distant location, pointing to Solar System evolution models that work better with an extra primordial ice giant. The 'five-planet Nice model' includes the premise that Uranus and Neptune formed in between Jupiter and Saturn before ejection. "If you add a fifth ice giant to that scenario, it's much more likely that Uranus and Neptune would remain in our Solar System," says Rogoszinski.

If Scholtz is right and capture is most likely, then the PBH hypothesis would clearly benefit from proof these objects exist in abundance. Niikura suggests comparing microlensing events observed towards the galactic centre – where both rogue planets and PBHs are thought to be prevalent – with data from the Large Magellanic Cloud. This local satellite galaxy is relatively depleted in planets, so the contribution from PBHs could be teased out.

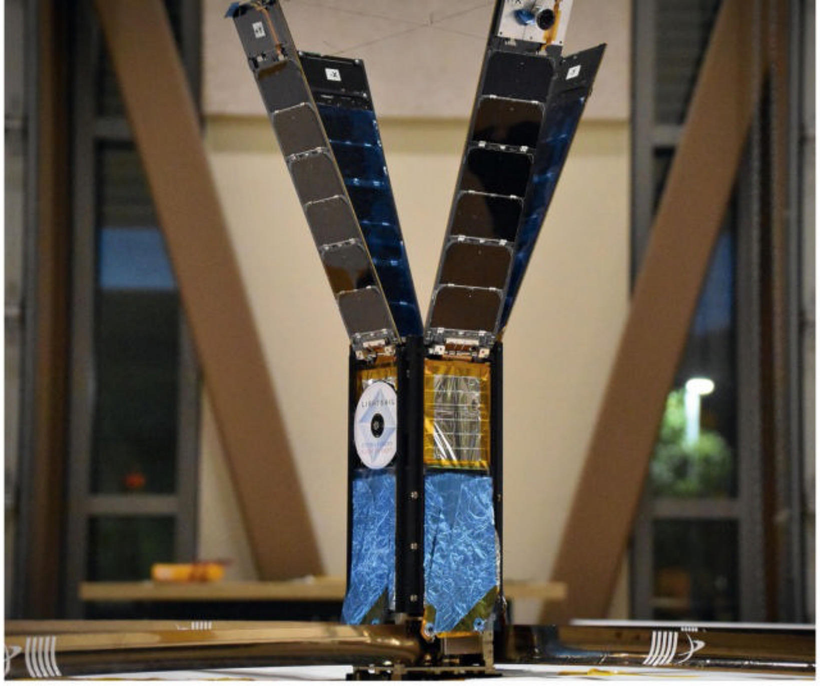
Building this theoretical case seems sensible. And yet, with a potential black hole inside our Solar System, it is not surprising Scholtz's paper inspired a host of mission concepts aiming straight for this mysterious gravitational heavyweight. "It seems obvious that if there is a black hole in the outer Solar System, we want to find it," says Witten. He was first off the mark with a concept for laser-propelled, lightweight spacecraft attached to lightsails. Based on the Breakthrough Starshot concept to reach our nearest star Alpha Centauri, Witten suggested launching hundreds of craft spreading out along our Solar System's orbital plane. Unlike the Starshot craft, Witten's would carry an atomic clock and a transmitter. This additional weight would mean a decade-long journey, but would allow each craft to alert us if they encounter a planet or black hole through their acceleration.

Others proposed improvements to Witten's proposal. In his own paper, Rogoszinski scrapped the weighty clock and suggested looking for bends in a craft's trajectory from the same gravitational influence. Harvard theoretical physicist Avi Loeb thought both approaches failed to address the noisy environment inside which our target likely resides. "Once you go past about a hundred AU you're battered by the interstellar medium," explains Scholtz. "For a precision mission this could be a serious hurdle."

Loeb proposed a longer mission, sending craft weighing a kilogram or more to minimise drag. This added weight could also allow for instruments to differentiate between a planet and a black hole. However, if such a multi-decade trip doesn't appeal, a laser-shot mission will be limited to locating our elusive gravity source. Then Earth telescopes can at least focus down on a particular patch of sky where a distant planet might be teased out eclipsing background stars. "If it's a black hole the size of a baseball, we wouldn't be able to observe any occultations," points out Rogoszinski.

**Right:** **Proposals to reach Planet Nine are based on lightsail technology**

**Below:** **The Kuiper Belt is made up of scattered debris left over from planetary formation**



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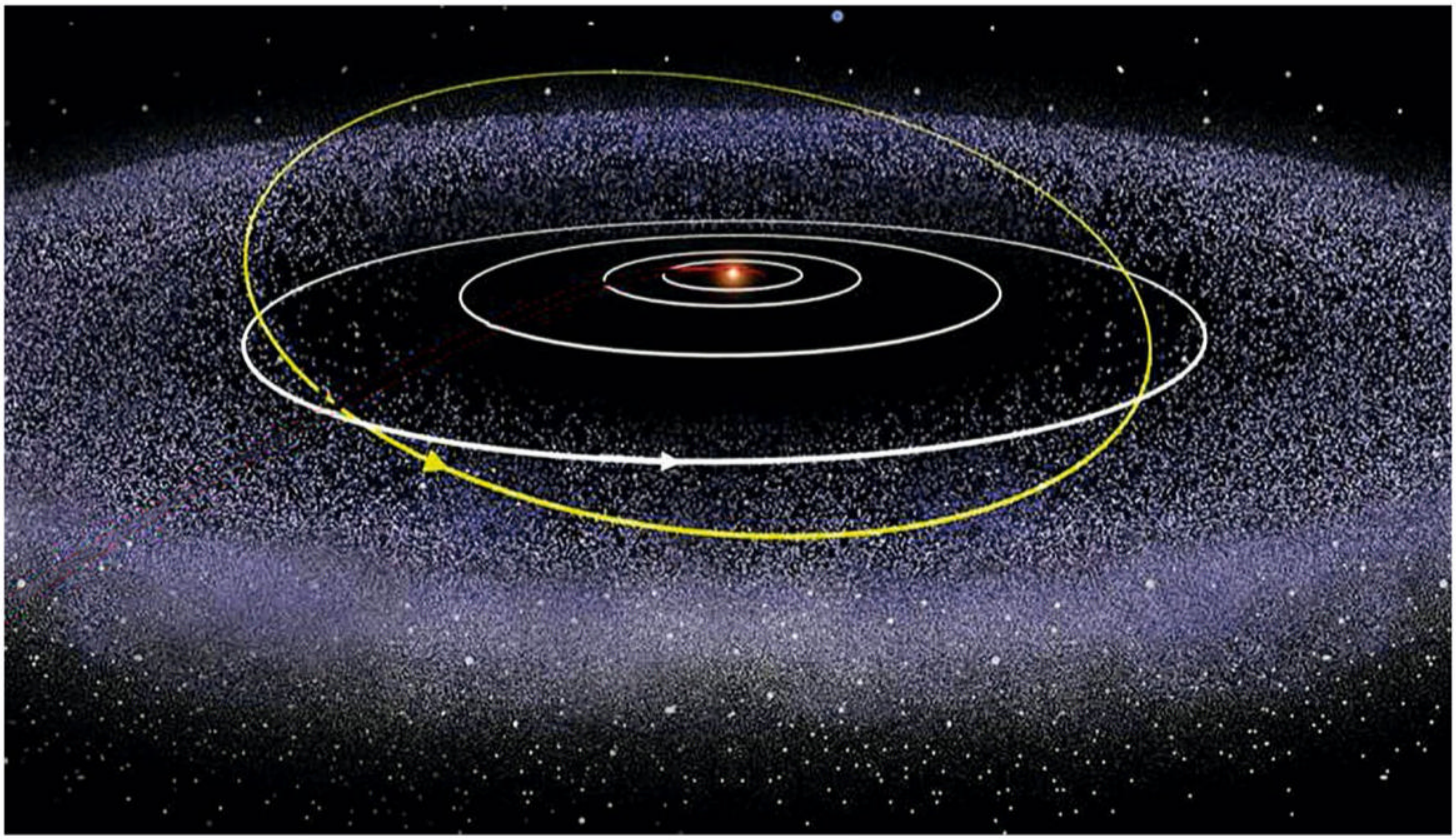

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# A breakthrough in reaching the outer Solar System

How a mission to Alpha Centauri has inspired an approach to pinpoint our mysterious outer Solar System object

### 1 Light beam transportation

In the 1960s it was suggested the newly invented laser could accelerate armies of ultralight sail-bound craft a substantial fraction of the speed of light, opening up interstellar travel – or a fast way to reach the outer Solar System.

### 3 A perfect mirror

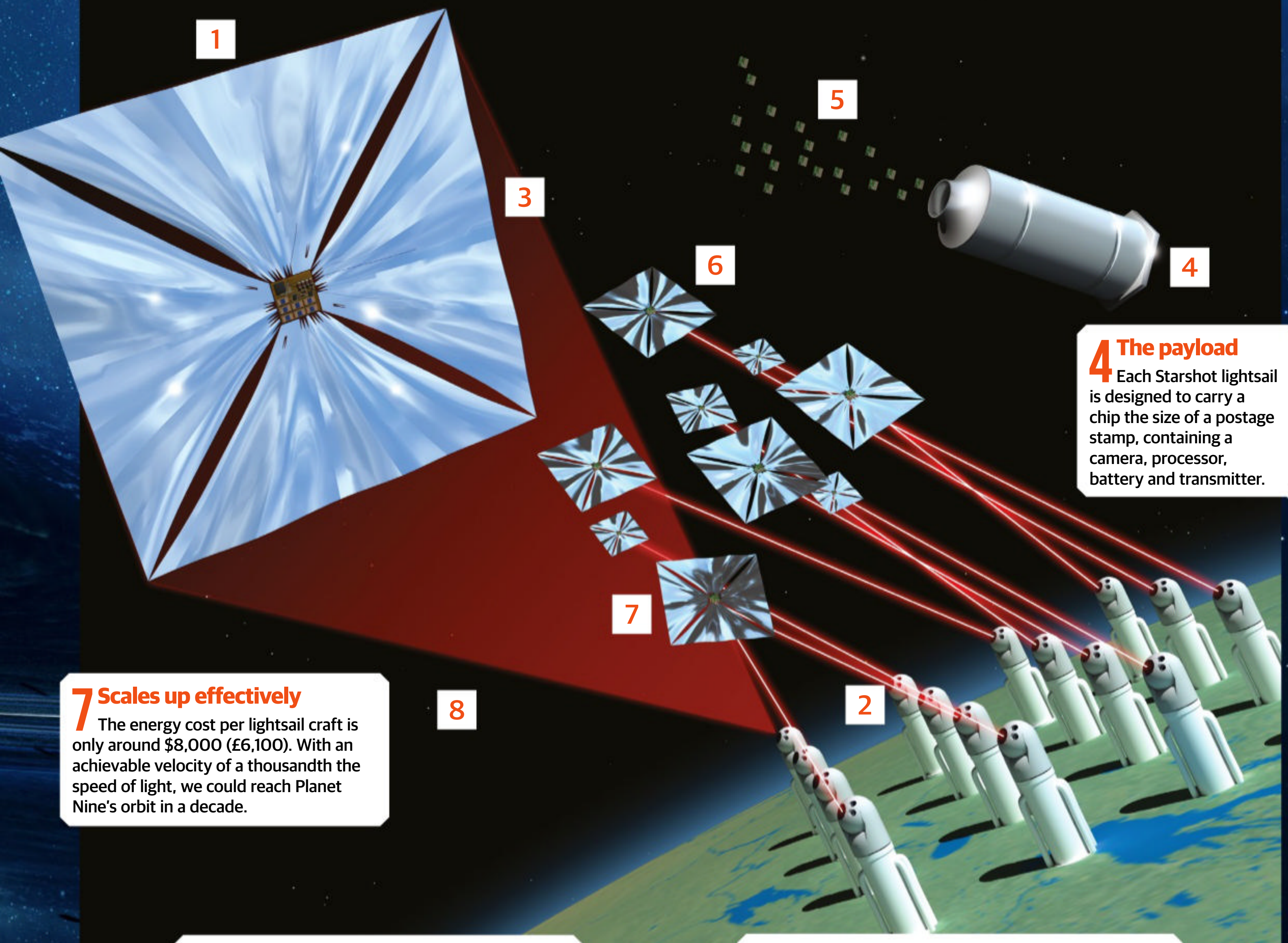
Each proposed lightsail is four metres (13 feet) across, but just a few hundred atoms thick. The sail material needs to be an almost-perfect mirror, reflecting 99.99 per cent of the photons that reach it, otherwise the lasers will burn it up.

### 5 Hedging your bets

With no clues where around its proposed orbit Planet Nine or our black hole might be, Starshot's safety in numbers approach to space travel would see hundreds of spacecraft launched in various directions.

### 6 Sensor network

In Ed Witten's Starshot-inspired proposal to find Planet Nine, each craft is fitted with an atomic clock, broadcasting time signatures. Any craft on the right path will accelerate due to our target's gravity, lengthening the gaps between signals received on Earth.



### 4 The payload

Each Starshot lightsail is designed to carry a chip the size of a postage stamp, containing a camera, processor, battery and transmitter.

### 7 Scales up effectively

The energy cost per lightsail craft is only around $8,000 (£6,100). With an achievable velocity of a thousandth the speed of light, we could reach Planet Nine's orbit in a decade.

### 8 Narrowing down the search

Once Planet Nine is found by the brute force method, subsequent, more focused searches could pin down its location far more precisely, and perhaps make a close-up study of the object.

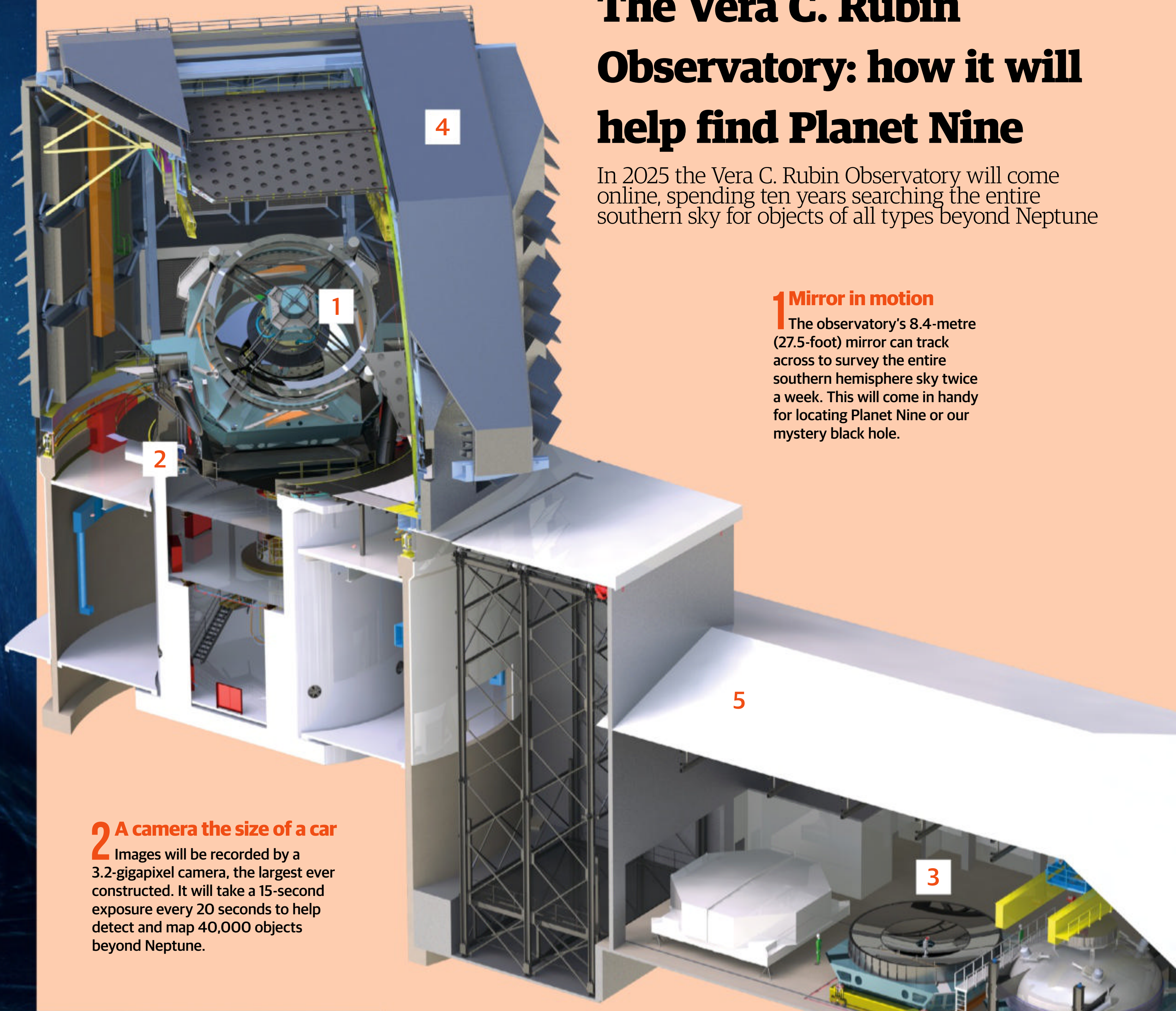
### 2 Point your lasers to the sky

Light propulsion requires enormous power. Current plans to reach our nearest star are based around a one-kilometre (0.6-mile) wide grid of lasers firing a gigawatt of laser energy into the sky.

© Adrian Mann

# The Vera C. Rubin Observatory: how it will help find Planet Nine

In 2025 the Vera C. Rubin Observatory will come online, spending ten years searching the entire southern sky for objects of all types beyond Neptune



### 1 Mirror in motion

The observatory's 8.4-metre (27.5-foot) mirror can track across to survey the entire southern hemisphere sky twice a week. This will come in handy for locating Planet Nine or our mystery black hole.

### 2 A camera the size of a car

Images will be recorded by a 3.2-gigapixel camera, the largest ever constructed. It will take a 15-second exposure every 20 seconds to help detect and map 40,000 objects beyond Neptune.

**Left:** The Vera C. Rubin observatory will map the outer Solar System with the world's largest digital camera

© ISST Project

### 3 Onsite maintenance

To maximise imaging time for characterising 100 times more TNOs than are currently known, the observatory has a cleaning and coating area where mirrors are washed and recoated.

### 4 Keeping the mirror cool

The telescope's sensitivity is maintained by cooling the mirror temperature. This could allow for the detection of flares given out if our primordial black hole consumes a passing comet.

### 5 At home in its environment

The observatory's orientation was selected after extensive testing to minimise air disturbance, giving some confidence that it will be able to detect brightness variations, measure TNO colour and infer composition.

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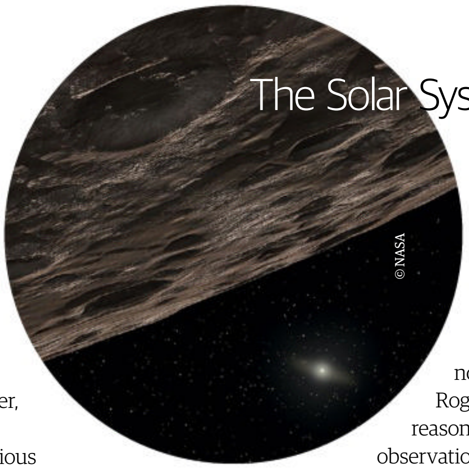
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In the meantime, Scholtz highlights a potential signal that could tip the planet-black hole scales towards the latter. While primordial black holes disappointed as dark matter, we'd still expect one to be surrounded by the mysterious substance. Indeed, Scholtz calculated his PBH would have a five-centimetre (1.9-inch) radius and come with a dark matter halo extending out a billion kilometres. "In most scenarios dark matter can annihilate and form visible signals," says Scholtz, who suggests it's possible we've seen halo signals within observations of the Fermi Gamma-ray Space Telescope. Though he admits it's one thing collecting this data, it's another teasing it out from its billion-photon database.

Unfortunately, whether it's dark matter annihilations, starfield occultations or spacecraft gravitational deflections, this mystery in the outer Solar System isn't giving up its secrets easily. But Scholtz sees the positives in the fact his theory can simultaneously explain two anomalies. Others still need some convincing.

"The odds are it's probably not a black hole," says Rogoszinski, who sees many reasons why this object has eluded observation without it being a tiny black hole. "Maybe its reflectance is very low, or maybe there are no stars behind it to occult?" However, he admits that if searches continue to draw blanks, at some point the probability will begin to shift. Zurek is in agreement. "I think it's probably not [a black hole], but it's not really ruled out. If there's an existing instrument, let's have fun."

Fun is one way to describe such a discovery. Scholtz goes with 'staggering' and a few other effusive terms. "To be able to experiment with the black hole, that would be a dream come true. We could really understand a lot about gravity, about general relativity, but also about quantum mechanics. It would be a new window into science."

> "If Planet Nine is a conventional planet, I think it is expected to be discovered by the Vera Rubin Observatory" **Ed Witten**

**Above:** Eccentric Kuiper Belt orbits are often influenced by both the inner and outer Solar System

**Right:** The OGLE facility may have spotted the fingerprints of primordial black holes within its starfield

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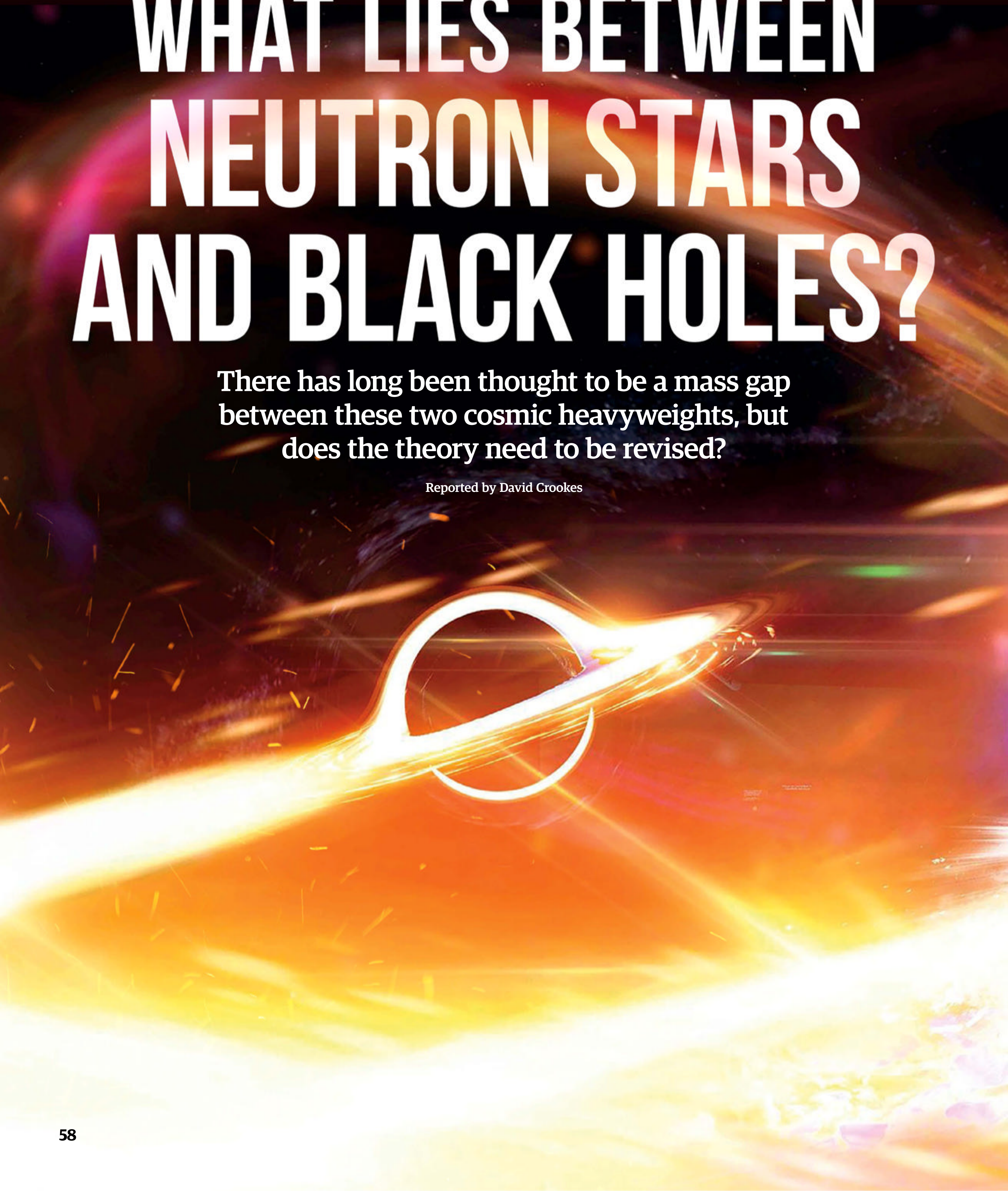
MYSTERIES OF THE UNIVERSE

# WHAT LIES BETWEEN NEUTRON STARS AND BLACK HOLES?

There has long been thought to be a mass gap between these two cosmic heavyweights, but does the theory need to be revised?

Reported by David Crookes



Scientists know about neutron stars. They're very much aware of black holes, too. But what if there's something in between? This is what astronomers are pondering having discovered a cosmic event called GW190814. It was found through the detection of gravitational waves on 14 August 2019, and involved an object of a mass that had never been seen before.

Up to that point, the heaviest known neutron star was found to have a solar mass of 2.3, with the lightest known black hole being about five solar masses. Yet GW190814 pointed to an object of 2.6 solar masses, making it either the heaviest neutron star ever seen, the lightest black hole or perhaps even something else entirely. It's so significant that it's set to change how we look at neutron stars and black holes, not least because it poses a great challenge to our current theoretical models.

For years astronomers have worked on the assumption of a 'mass gap' to explain why there are no objects with a solar mass greater than 2.3 or less than five. But now that an object involved in the GW190814 event sits firmly within the gap, albeit at the lower end, that assumption must be

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## THE MASS GAPS

### BY THE NUMBERS

**2.6**

Size in solar masses of the discovered object

**23**

Size in solar masses of the black hole

**3,000**

Number of kilometres between the two detectors making up LIGO

**2019**

Year the object was discovered, on 14 August

**20**

Diameter of a neutron star's core in kilometres

**8 BILLION**

tonnes in a single teaspoon of neutron star matter

**800,000,000**

light years to the object's location from Earth

**6X**

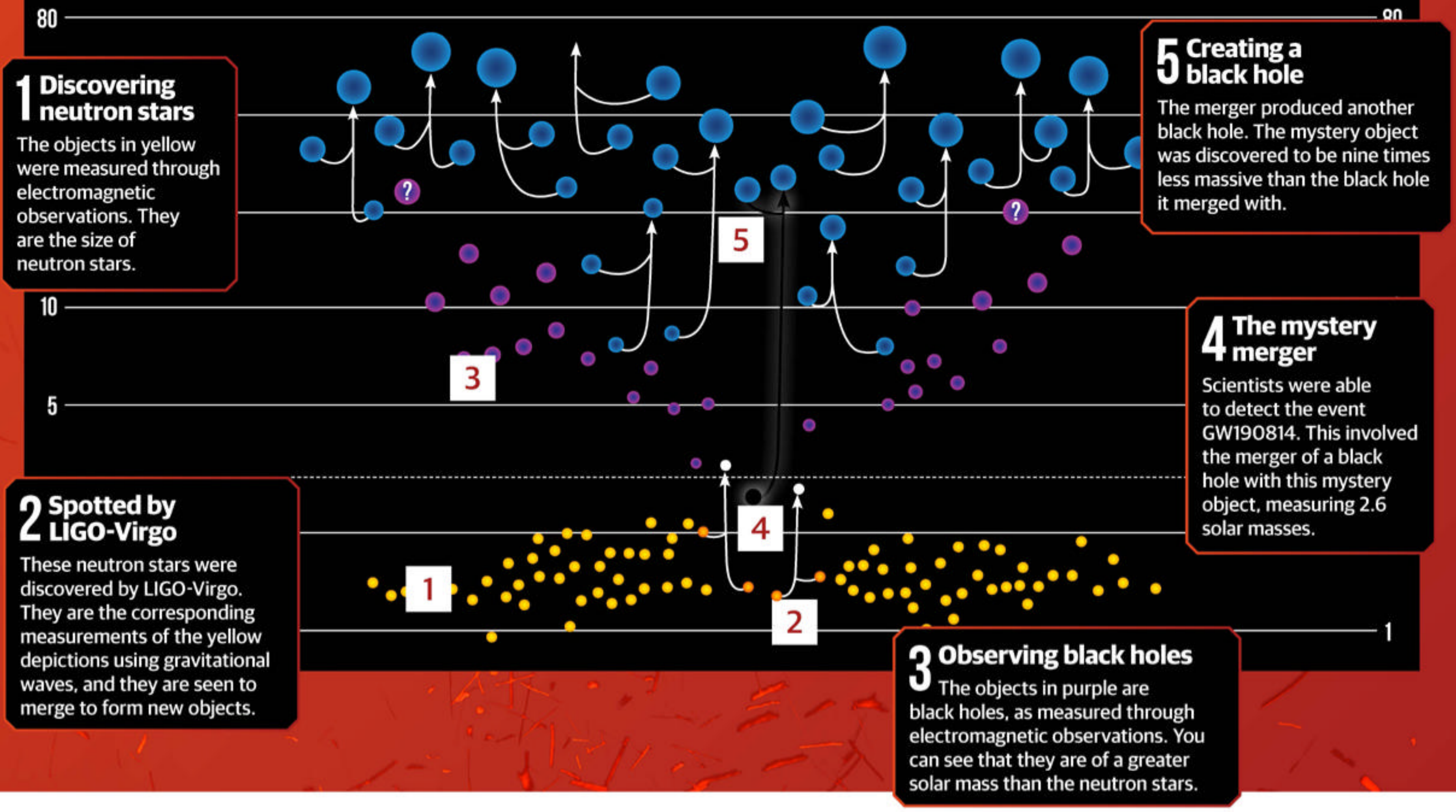
farther away than a merger discovered in 2017

**25**

Size in solar masses of the final black hole produced by the merging of the two objects

# Observing collision events

LIGO-Virgo has been key to the discovery of many mergers through the detection of gravitational waves



**1 Discovering neutron stars**
The objects in yellow were measured through electromagnetic observations. They are the size of neutron stars.

**2 Spotted by LIGO-Virgo**
These neutron stars were discovered by LIGO-Virgo. They are the corresponding measurements of the yellow depictions using gravitational waves, and they are seen to merge to form new objects.

**3 Observing black holes**
The objects in purple are black holes, as measured through electromagnetic observations. You can see that they are of a greater solar mass than the neutron stars.

**4 The mystery merger**
Scientists were able to detect the event GW190814. This involved the merger of a black hole with this mystery object, measuring 2.6 solar masses.

**5 Creating a black hole**
The merger produced another black hole. The mystery object was discovered to be nine times less massive than the black hole it merged with.

**Left:** An artist's impression of two black holes - one nine times more massive than the other - spiralling into each other and colliding

© Max Planck Institute for Gravitational Physics) SXS

revised. "The mass spectrum is not thought to be continuous - there are gaps in it," explains Dr Laura Nuttall, senior lecturer in gravitational waves at the University of Portsmouth's Institute of Cosmology and Gravitation.

"At the lower end we have black holes with masses about the same size as the Sun - they're called solar mass black holes. At the higher end we find black holes with masses that are millions of times that of the Sun, called supermassive black holes. When people talk of the mass gap, they may be referring to the realm between neutron stars and black holes. For a while we haven't known if this gap is real, or whether there is a continuous spectrum and our instruments haven't been able to see any yet." Little wonder the object involved in GW190814 is being seen as a game changer. Maybe there is no mass gap after all.

> "For a while we haven't known if this gap is real, or whether there is a continuous spectrum"
>
> **Laura Nuttall**

Before we look more deeply into this mystery, however, it's worth refreshing our minds about the difference between neutron stars and supermassive black holes. Both are formed when a massive star dies and explodes, resulting in the small, dense core that's left behind gradually collapsing under its own gravity. As it does so, protons and electrons are crushed together into a neutron, and if the core is less than three solar masses, a dense, dead remnant - the neutron star - will remain.

If the mass is great enough, however, the collapse will become more severe, and this will lead to a black hole. But why do lighter cores form neutron stars and those from heavier ones form black holes? Nuttall, whose gravitational-wave group played a key role in the study along with other universities across the world, explains: "It's all to do with mass. When a massive star collapses, we usually think that either a neutron star or black hole forms, but you might be better thinking that they will all form a neutron star first.

"If more mass is then added to the neutron star because of the collapse of the star, there will be a limit at which the neutron star can be stable. This is to do with 'neutron degeneracy' - the pressure which the neutron star fights against gravity - and it's down to quantum physics. "Here no neutrons can exist in the same quantum state, but if you try to add more and more mass to this object, at some point the neutron star will become unstable and collapse further into a black hole."

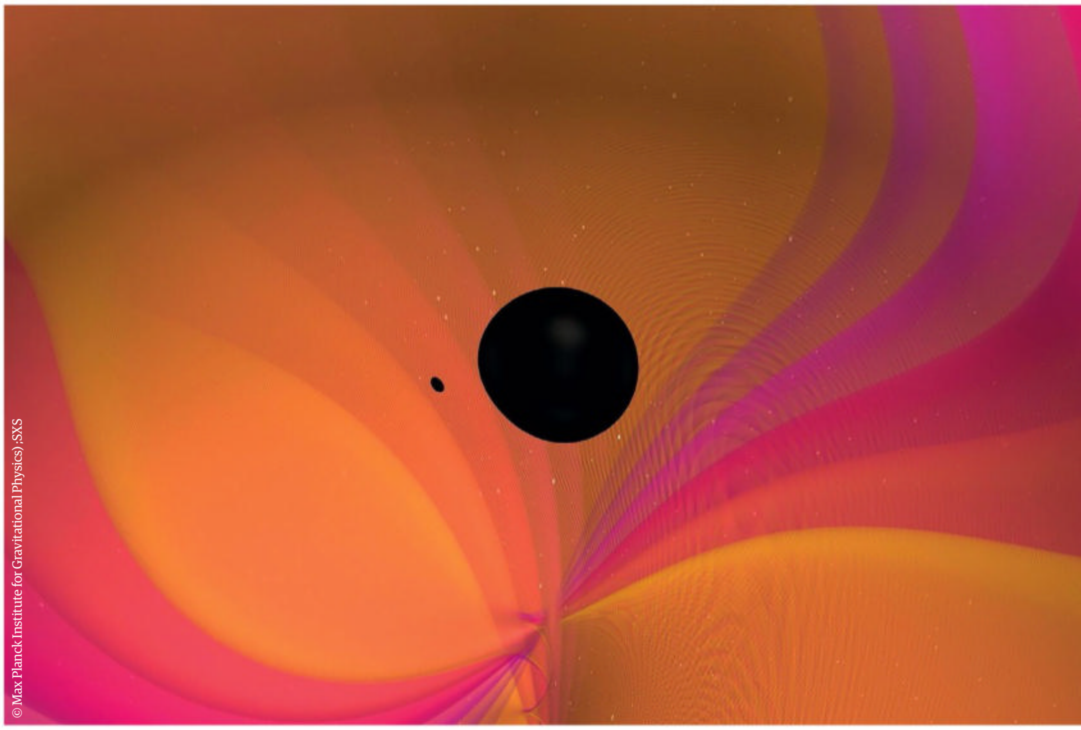
When neutron stars and black holes merge or collide, it results in gravitational waves. And over the past five years these have been detected. Indeed, in 2017 and 2019, observations were taken of two sets of colliding neutron stars, with the resulting ripples in space-time – predicted by Albert Einstein 99 years earlier – being picked up by the National Science Foundation's Laser Interferometer Gravitational-Wave Observatory (LIGO).

Space-time ripples have also been observed from merging black holes, and such discoveries have been a huge justification for creating LIGO. It began collecting data in 2002 from its two detectors: one in Livingston, Louisiana, and the other in Hanford, Washington. They are 3,000 kilometres (1,864 miles) apart, and in the case of GW190814 were used in combination with the Virgo detector in Italy. But what actually happened during GW190814? There was a merger of an object with a black hole containing 23 solar masses of material, and it was discovered that prior to this merger the other object's mass differed by a factor of nine, making it the most extreme mass ratio for a gravitational-wave event yet. It resulted in a final black hole 25 times the mass of the Sun, with some of the mass converted to gravitational waves. Scientists say it is about 800 million light years away from Earth, but they're not entirely sure how to identify the object involved in the merger with the black hole.

"The mystery object may be a neutron star merging with a black hole, an exciting possibility expected theoretically but not yet confirmed observationally," says Professor Vicky Kalogera from Northwestern University in Evanston, Illinois. "However, at 2.6 times the mass of our Sun, it exceeds modern predictions for the maximum mass of neutron stars, and may instead be the lightest black hole ever detected."

Nuttall is erring towards the mystery object being the latter. "Right now it's looking like a light black hole – or at least the simplest explanation is a really light black hole," explains Nuttall. Even then, though, there are many more questions, not least if light black holes can indeed exist. Remember, this one would be just 2.6 solar masses compared the previously lightest black hole of no less than five solar masses. If this is the case, then how are they forming? "Are they being produced from the mergers of neutron stars or from stars collapsing?" Nuttall says of the conundrum. And the answer? "The jury is still out."

For how long is anyone's guess. Since the merger was discovered, the astronomical community has been in full swing, using ground- and space-based telescopes to search for any light waves that would have been generated. It's no easy task, especially given that light waves resulting from a gravitational wave event have only ever been spotted once before, back in August 2017 when two neutron stars spiralled closer to each other, collided and finally merged. The gravitational-wave signal lasted 100 seconds, but 11 hours later a fast-moving, rapidly cooling cloud of neutron-rich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**Above:** A visualisation of the coalescence of two black holes merging and emitting gravitational waves – one nine-times more massive than the other

**Below:** Kalogera compares the merger involved in GW190814 to "Pac-Man eating a little dot"

# The theories

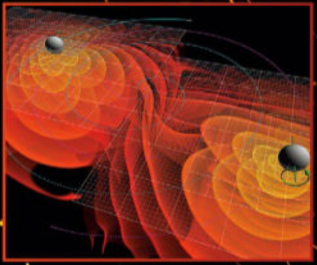
What could the mystery object discovered

## Heaviest neutron star

© NASA

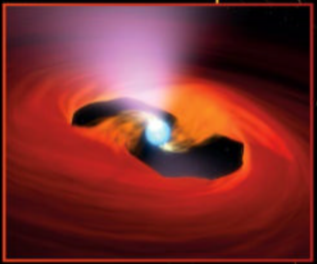
Since the object's measurements place it at the lower end of the mass gap, it is closer in size to neutron stars than black holes. However, at 2.6 solar masses, it exceeds the limit for a neutron star's maximum mass. This was thought to be 2.3, but astrophysicists at Goethe University Frankfurt set it as low as 2.16 in 2018. Most neutron stars have a mass of 1.4 solar masses.

## Lightest black hole


© NASA

The most favoured explanation is a black hole, because no light was detected during the event of August 2019. This theory works because two merging black holes would not produce any light. But this could also be due to the object being too far away. A neutron star with nine times less mass than the black hole would also be gobbled up in one, again producing no light.

## Rapidly spinning neutron star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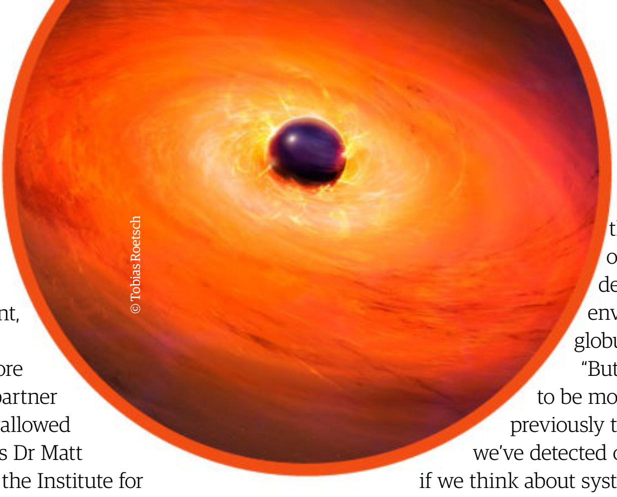
Maya Fishbach, a member of the LIGO Scientific Collaboration, says we can't dismiss this theory. "Mainly because I think that would be really cool," she tells us. A rapidly spinning neutron star would be able to support more mass: the maximum of 2.3 solar masses refers to a non-spinning case. "It would have to be spinning pretty quickly, though," she adds.



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material ended up being observed by dozens of telescopes. This event, GW170817, was considered to be the biggest breakthrough of the year.

The difference between GW170817 and GW190814, however, is that a collision between two neutron stars is expected to give off light. When an object merges with a black hole, though, the situation isn't quite as straightforward - black hole mergers are not thought to produce light. Given those circumstances, it's perhaps no surprise to learn that optical or infrared radiation hasn't been detected. Does this entirely rule out a neutron star?

No, but in truth the evidence stacks against it being one. Astrophysicists work on the assumption that there should be an absolute upper limit for the mass of a cold, self-gravitating body, and this manifests itself as the Tolman-Oppenheimer-Volkoff limit. It's the point at which the core of a neutron star becomes so massive that neutron pressure is overwhelmed by gravity, leading the object to collapse into a black hole. That limit is calculated to be no more than 2.4 solar masses.

Is this why light isn't being emitted? Not necessarily. The black hole in GW190814 was nine times larger than the other object, which means whatever collided with it is likely to have been gobbled up in a cosmic instant, preventing any light from shining. "Its more massive black hole partner may have simply swallowed it up whole," explains Dr Matt Nicholl, a lecturer at the Institute for Gravitational Wave Astronomy at Birmingham University, UK.

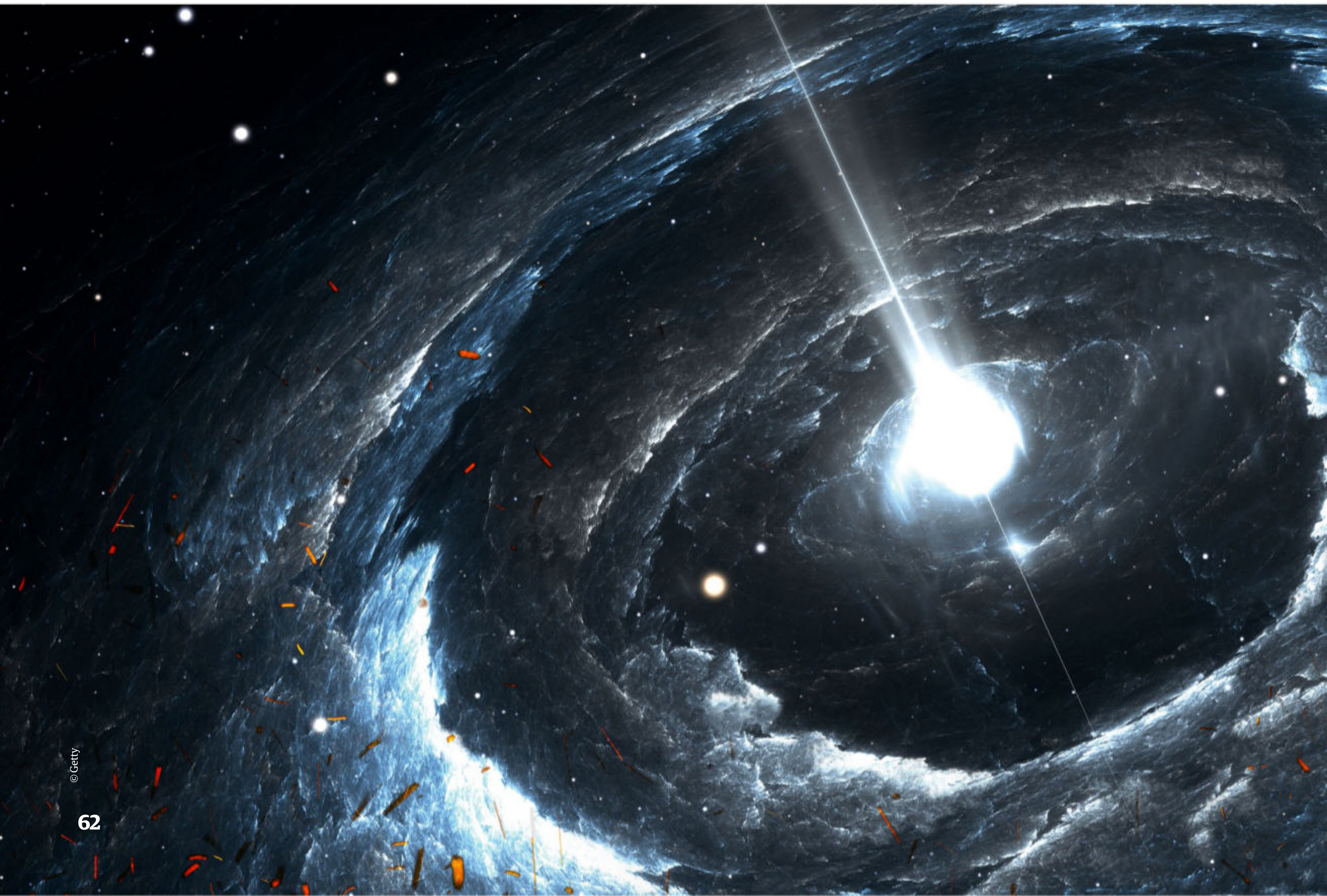
GW170817 was also six times closer to Earth, which made it easier to pick up on any light. But it does look more likely to be a small black hole, and all researchers can do is look out for similar collisions pointing to objects within the mass gap. Is that possible? Surely the evidence is now suggesting that the object involved in GW190814 isn't the only one, but there must still be a reason why we're just not seeing them. "In terms of gravitational waves, there could be a few reasons," affirms Nuttall. "First, it seems quite hard to make a system like GW190814: it has a high mass ratio - a small object with a larger object - and it's typically thought that these objects form in dense gravitational environments like globular clusters.

"But they do seem to be more common than previously thought, since we've detected one system. Now if we think about systems with similar masses, then smaller mass systems will need to be closer for us to detect. The heavier objects are, the larger the amount of gravitational waves that are given off. "We may just need to wait for more sensitive instruments. On the electromagnetic side of things I think this is also the case. There could be a selection effect going on."

One thing's for sure: odd instrumental behaviour has been largely ruled out. The object in the GW190814 event really does appear to be 2.6 solar masses. It's also the only one scientists have ever observed to be within the mass gap, even though GW170817 was found to have created an object of 2.8 solar masses when the neutron stars collided.

"We're not sure from the gravitational wave side what this remnant was because the data isn't good enough. In the future we hope that our detectors will become sensitive enough to measure a post-merger signal," says Nuttall. "But astronomers have looked at X-ray data from GW170817, and I think the consensus currently is that a long-lived neutron star was created and then collapsed into a black hole."

"The mystery object may be a neutron star merging with a black hole" **Vicky Kalogera**



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Astronomers are learning a lot about the dynamics of stars, and they are at the beginning of discovering what gravitational waves can tell them about the mass gap. With LIGO, many more breakthroughs are expected, and scientists are excited by the possibilities. "In only five years we have observed 13 black hole mergers and two neutron star collisions, and we have yet to tell the world everything about the third observing run, which concluded in March 2020.

"We are starting to understand more about black holes and neutron stars, and how this feeds back to how stars live and die. We know black holes that are tens of times the mass of the Sun exist. We know that right now everything follows general relativity, and that neutron star collisions produce short gamma-ray bursts and are a site for the production of heavy elements.

"We're now starting to detect objects in this mass gap, and they look like black holes. Over the next few years the LIGO, Virgo and the Kamioka Gravitational Wave Detector in Tokyo are going through upgrades to increase sensitivity, and will start listening to the universe again in 2022. What else are we going to find?"

**David Crookes**
*Science and technology journalist*
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.

**Left:** A small black hole could have formed from a previous neutron star merger event

**Below:** Black holes tend to be about five times the mass of the Sun, so a black hole at 2.6 solar masses is certainly intriguing

# What gaps in our knowledge remain?

Maya Fishbach is a postdoctoral fellow at Northwestern University and a member of the LIGO Scientific Collaboration

**Could there still be a mass gap?**

We still need more observations of compact objects before we can definitely conclude whether or not there is a mass gap - and where it is located. This is exactly what I'm trying to figure out with more gravitational-wave data from LIGO and Virgo.

My collaborators and I analysed the first 11 observations from LIGO and Virgo, which included ten binary black holes - with masses bigger than around seven solar masses - and one binary neutron star - with masses smaller than two solar masses. However, this was before GW190814, with the 2.6 solar mass object.

**What is the evidence showing?**

We found that based on those 11 data points, which included objects on both sides of the gap - but nothing in the gap - there was preliminary evidence for a mass gap. In other words, if there wasn't a mass gap, we would have expected to already have detected something in the two to seven solar mass range in the first two observing runs, and we didn't.

GW190814 definitely complicates this picture, but many options are still possible. There could be a mass gap between 2.7 solar masses and five solar masses, for example, instead of 2.2 solar masses to five solar masses. Or there might be a 'dip' in the mass distribution instead of a totally empty gap.

**On 17 August 2017, a signal was detected which appeared to suggest the discovery of an object of 2.8 solar masses. Is this in the mass gap?**

The 2.8 solar mass object detected in 2017 was the result of a collision between two 1.4 solar mass neutron stars. We don't know the fate of the final object from the gravitational wave signal, but there is evidence that the final object was a black hole. So yes, this object is definitely in the mass gap.

However, there is a key difference: the 2.8 solar mass object was formed from a merger of two neutron stars, not from a star undergoing a supernova explosion and collapsing into a neutron star or black hole. On the other hand, we think that the 2.6 solar mass object in GW190814 was formed directly from stellar collapse.

**Why do scientists think that this was the case?**

We don't expect that the merger product of two neutron stars could ever find another neutron star or black hole to merge with - although if this was how the 2.6 solar mass object formed, it would also be an exciting result. Prior to this observation, people thought that when stars undergo supernova explosions and collapse to a neutron star or black hole, something about the supernova mechanism would create a gap between the neutron star and black hole masses.

© LIGO

Alamy

> “Supermassive black holes that are found feeding hungrily on their surroundings are the workhorses of what scientists describe as active galaxies”

# Types of Black Holes

## From primordial to supermassive, meet the different types of black holes

**66** The power of supermassive black holes
Take a look at the engines that give these cores a high-energy boost

**74** Are primordial black holes really giant gravitinos?
It's a long shot of an idea, but when it comes to the early universe, it's the best we've got

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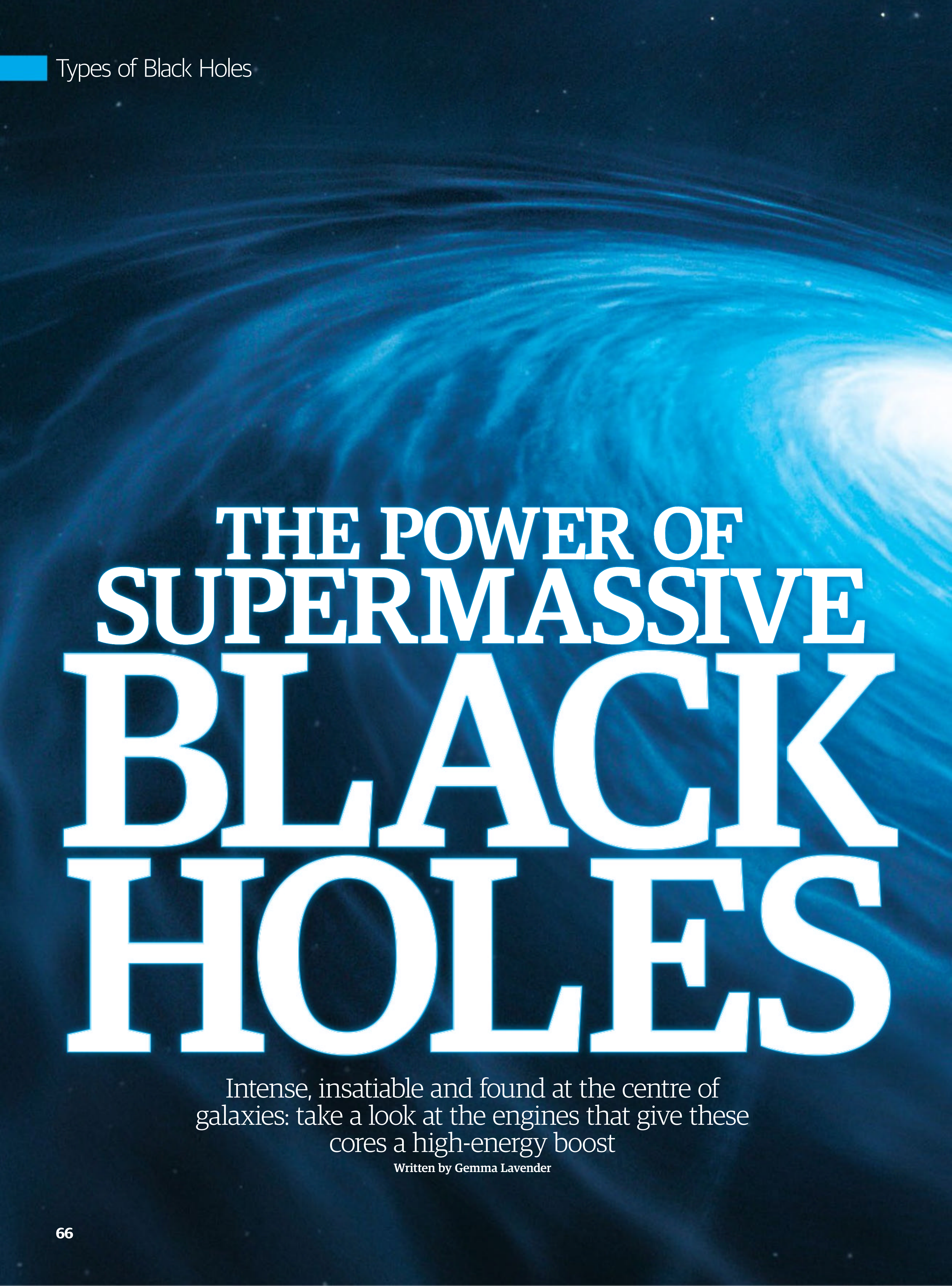
Did you know their event horizons make duckbill shapes?

**78** When black holes turn white
Can bouncing black holes help physicists find the ultimate theory of everything?



# THE POWER OF SUPERMASSIVE BLACK HOLES

Intense, insatiable and found at the centre of galaxies: take a look at the engines that give these cores a high-energy boost

**Written by Gemma Lavender**

The supermassive black hole is a formidable beast. Tipping the scales with a mass millions of times more than our Sun, this object wields incredibly strong gravity that's often the subject of fear in the workings of science fiction. It is the ultimate diner of the universe, concentrating only on satisfying its insatiable appetite and chomping down on any piece of space dust, gas or even stars, planets and asteroids that stray too close to its unworldly grasp.

To be clever at catching its cosmic prey, though, the supermassive black hole is akin to a spider positioning itself at the centre of its web. In this case the web is its galaxy around it and the black hole sits prestigiously in the centre, the perfect place to lie in wait for its next meal. From here it uses the universe as its home delivery service, where cosmic bites are brought straight to its edge. Millions of years can go by until it gets to chow down again but when it does, everything in the vicinity gets to know about it.

Bursts of brightness flash into existence and belches of speeding material shoot from these structures anytime the black hole gobbles up a snack. The bigger the meal, the longer these super-exotic objects keep their host galaxy awake, for thousands and thousands of years on end. To be accurate, it is not the black hole itself that is lighting up with every meal – not even light can escape a black hole's pull – but instead the environment immediately around the black hole, where the black hole's food gathers and heats up, waiting to either be swallowed into oblivion or blasted straight back out into space again.

Those supermassive black holes that are found feeding hungrily on their surroundings are the workhorses of what scientists describe as active galaxies; the black holes being the central engines that are so energetic they often shine bright enough to be regarded among the most luminous objects in the known universe. As a black hole siphons matter from nearby stars it uses its loot for the building blocks of a swirling disc of gas, known as an accretion disc, that encircles the black hole and is heated to amazingly hot temperatures of millions of degrees Celsius. Unable to keep a lid on its excitement, radiation spills from the black hole's vicinity in the form of powerful jets that extend great distances into space.

> "We're not sure why only some black hole systems produce powerful jets, but we're placing our bets on the spin"
>
> **Dr Alan Marscher, Institute for Astrophysical Research, Boston**

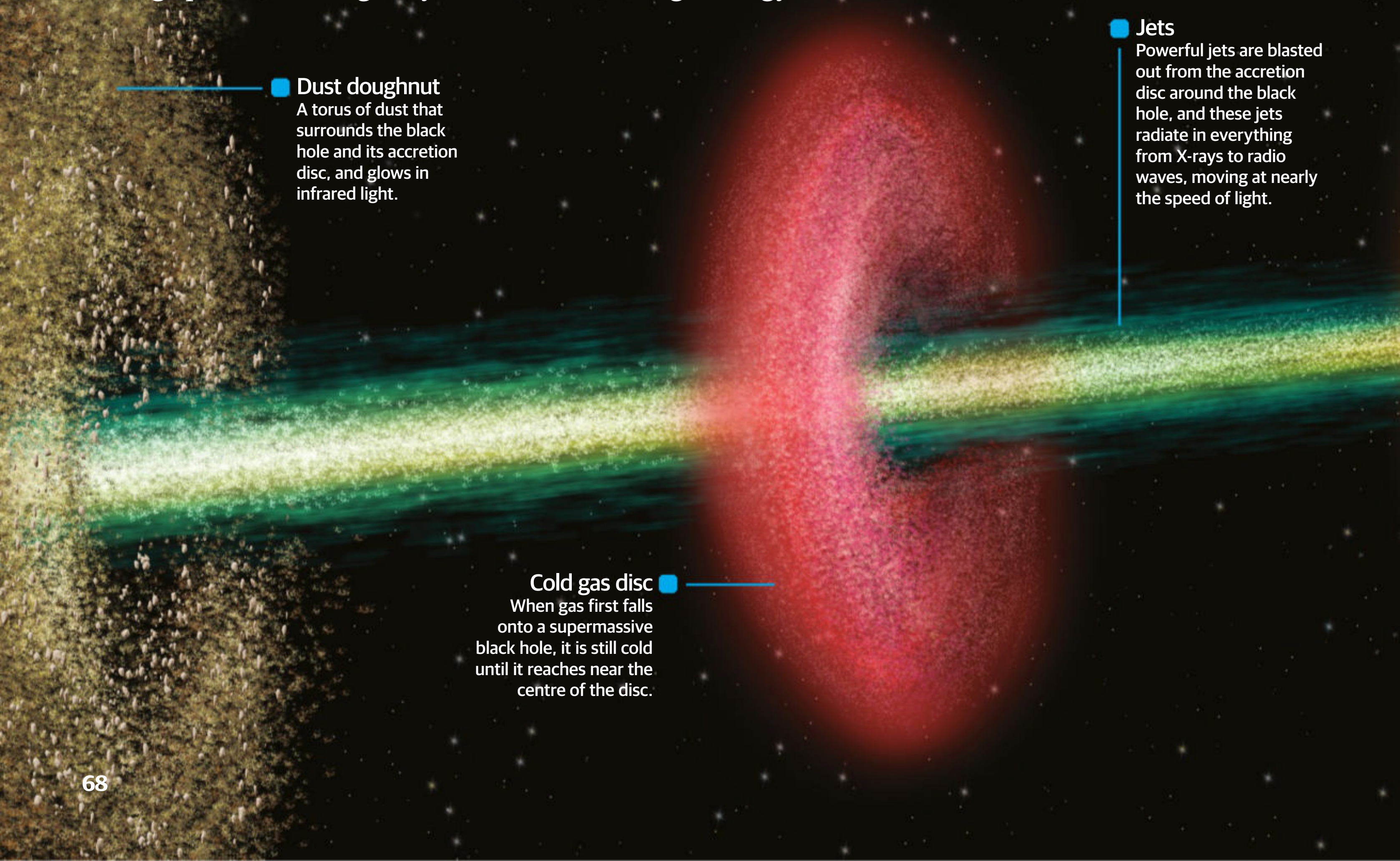
"Between five and ten per cent of active galaxies produce a pair of powerful, oppositely directed jets containing high-energy charged particles and magnetic fields," says Alan Marscher, who is currently based at the Institute for Astrophysical Research in Boston, USA. "We're not sure why only some black hole systems produce powerful jets but we're placing our bets on the spin of the black hole being an important determinant – high spins might twist up the magnetic field around the black hole so that the field acts like a coiled wire that creates a spring-like outward force on charge particles."

Marscher adds that when an active galaxy does spit out a stream of high-energy particles, a wide scope of energies across the electromagnetic spectrum are covered with particles being thrown out to smash their way through space in a variety of ways, more specifically in the flavours of radio, microwave, infrared, visible, ultraviolet, X-ray and gamma rays. That's not to say that the lower energy counterparts of active galaxies are afraid to pipe up in some wavelengths though. "In active galaxies without jets, the main radiation is across visible, ultraviolet and X-ray wavelengths, mostly from the disc of hot gas that is falling towards the black hole," says Marscher.

Despite radiating across the spectrum in all forms of light, active galaxies can be split into two camps displaying differing degrees of intensity according to their radio wavelength emission. These two camps are radio-loud and radio-quiet. The galaxies that belong to the radio-loud group sport two very high-

## The engine of a powerful galaxy

Pulling apart an active galaxy reveals a cosmic high-energy motor

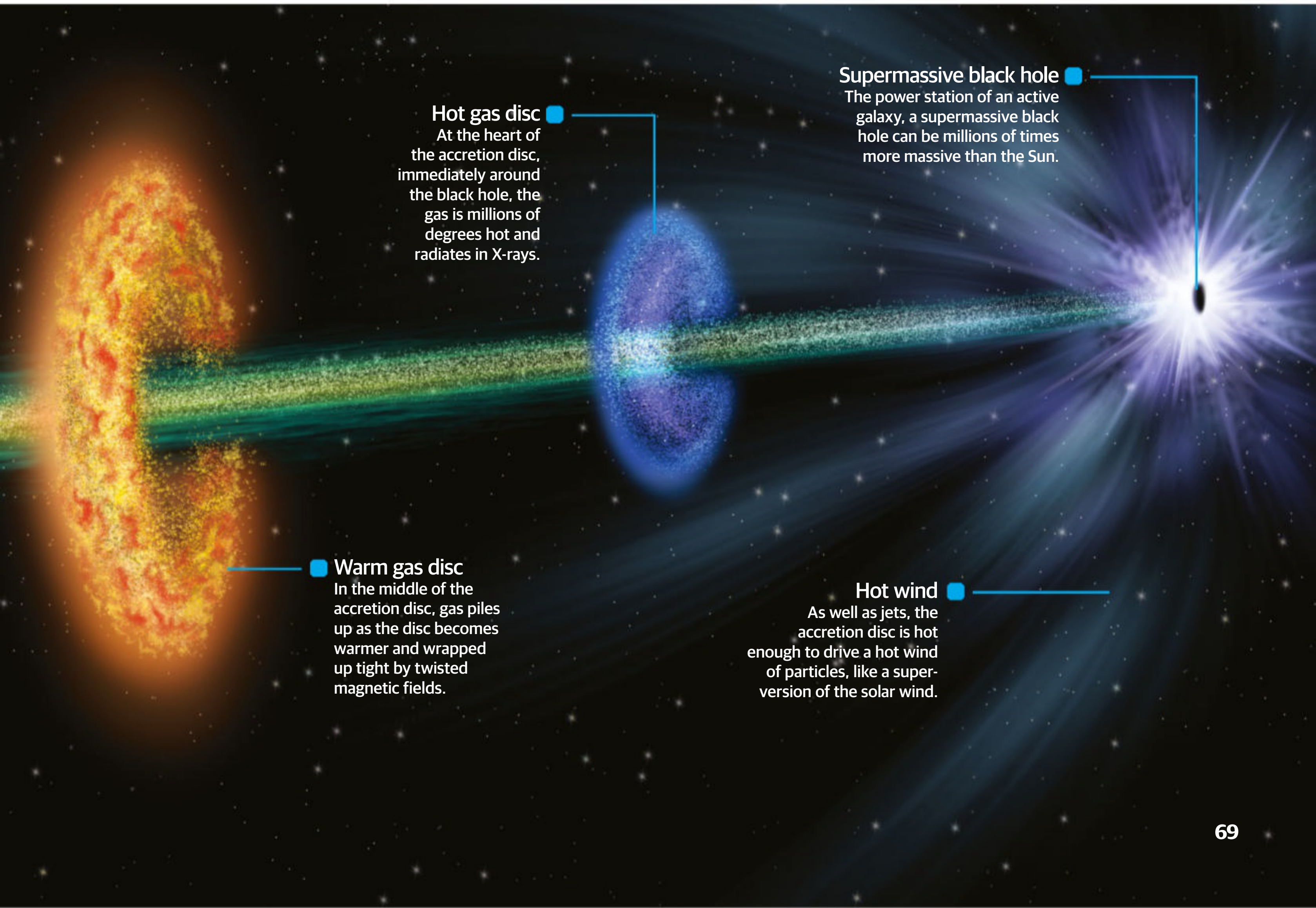


**Dust doughnut**
A torus of dust that surrounds the black hole and its accretion disc, and glows in infrared light.

**Jets**
Powerful jets are blasted out from the accretion disc around the black hole, and these jets radiate in everything from X-rays to radio waves, moving at nearly the speed of light.

**Cold gas disc**
When gas first falls onto a supermassive black hole, it is still cold until it reaches near the centre of the disc.

One of the closest active galaxies to Earth at a distance of around 13 million light years, Centaurus A ejects a powerful jet



**Supermassive black hole**
The power station of an active galaxy, a supermassive black hole can be millions of times more massive than the Sun.

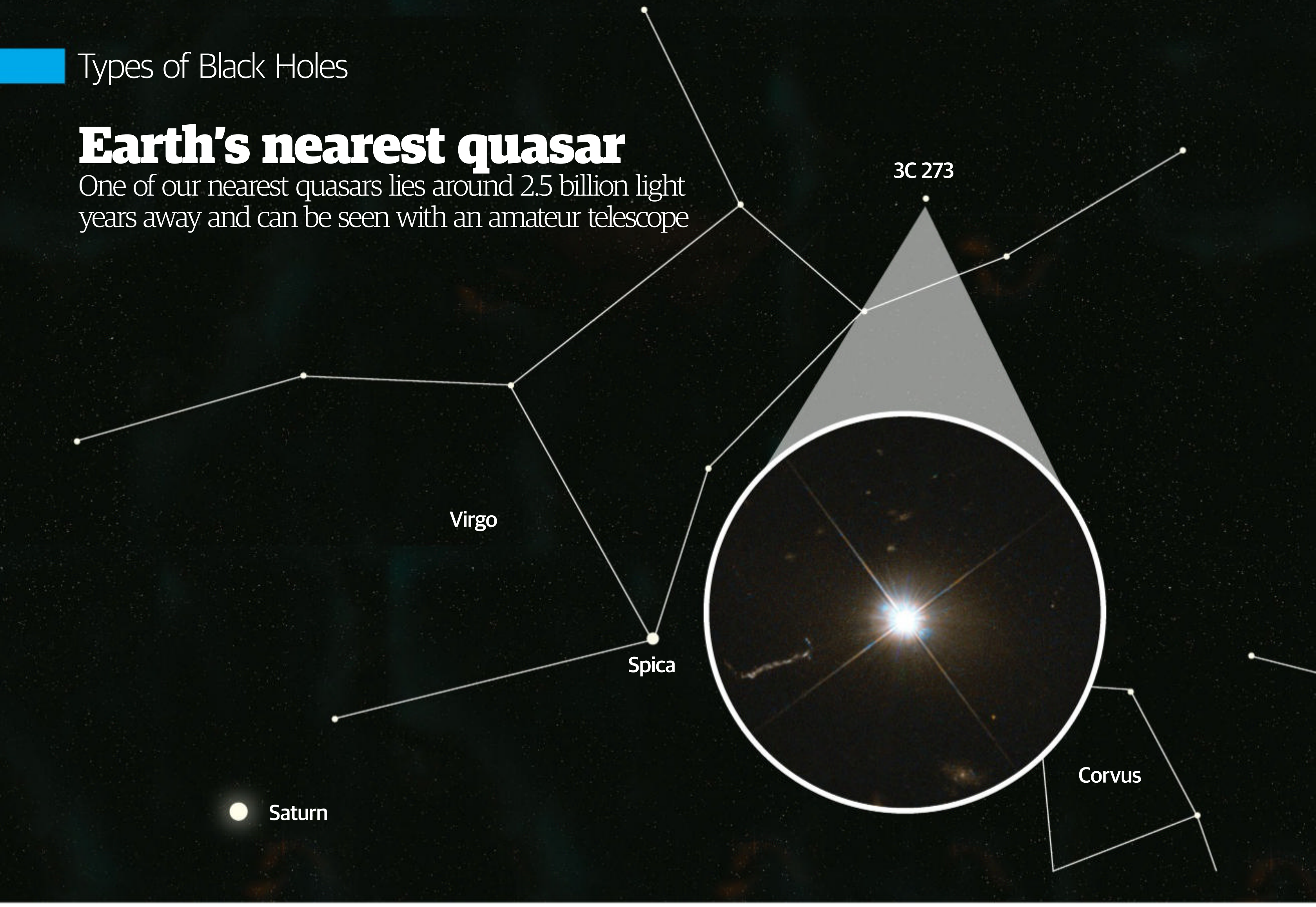
**Hot gas disc**
At the heart of the accretion disc, immediately around the black hole, the gas is millions of degrees hot and radiates in X-rays.

**Warm gas disc**
In the middle of the accretion disc, gas piles up as the disc becomes warmer and wrapped up tight by twisted magnetic fields.

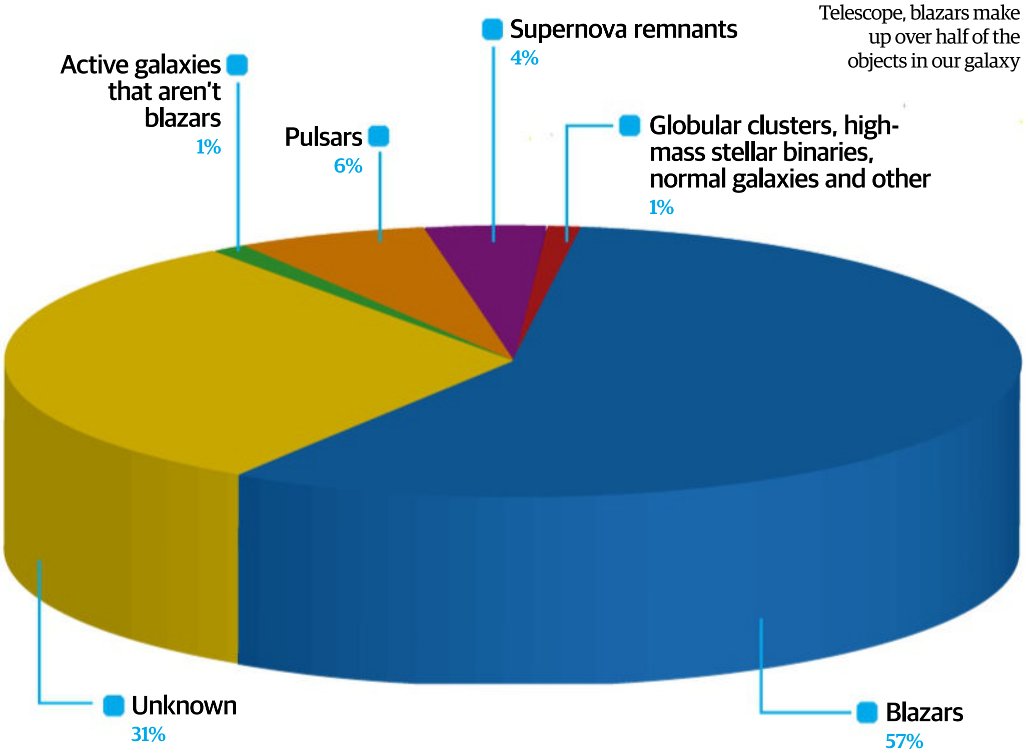
**Hot wind**
As well as jets, the accretion disc is hot enough to drive a hot wind of particles, like a super-version of the solar wind.

# Earth's nearest quasar

One of our nearest quasars lies around 2.5 billion light years away and can be seen with an amateur telescope



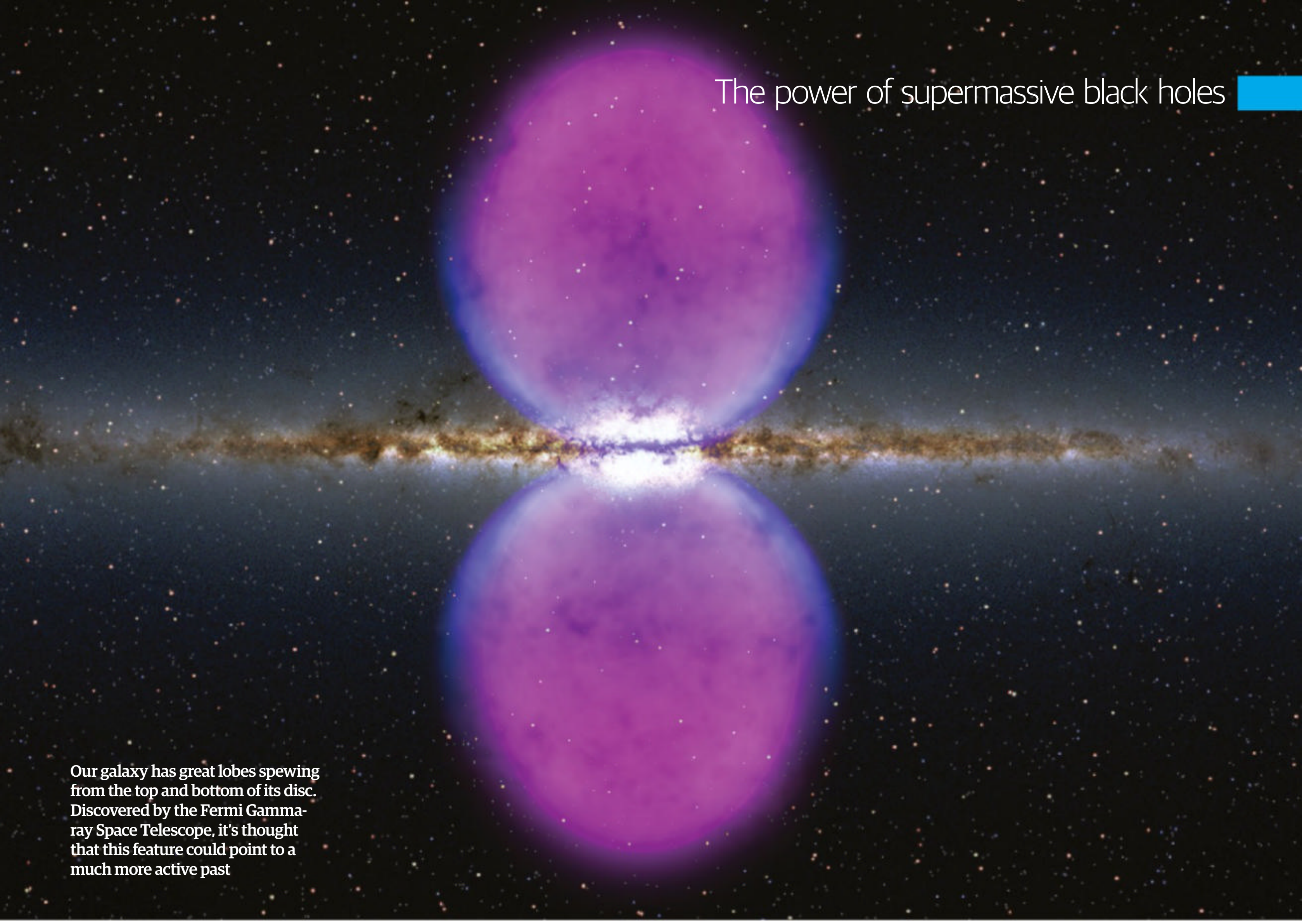
## Sources of extreme energy in space



According to the Fermi Gamma-ray Space Telescope, blazars make up over half of the objects in our galaxy

power streamers either side of the galaxy's disc, produced by the jets, which eventually inflate into a pair of lobes that emit strongly in radio waves, as well as other radiation like X-rays. The Centaurus A and Perseus A galaxies are two famous examples of radio-loud galaxies. The Milky Way galaxy has something similar, but on a much smaller scale and lower power. The Milky Way's lobes were not actually spotted through radio waves, but by a faint stream of gamma rays and X-rays seen by the NASA-owned Fermi Space Telescope. The cause of these lobes, or bubbles as they have come to be known, isn't certain but it's thought that the Milky Way was much more active in the past. Scientists think that millions of years ago, an intergalactic gas cloud weighing in at 10,000 times the mass of the Sun floated into and was devoured by the mega black hole, which we call Sagittarius A* (A-star), at the galaxy's heart. It responded by blowing gigantic bubbles and jets of radiation extending 27,000 light years above and below the plane of the galactic disc. Today, our galaxy is incredibly mellow in comparison to its previous wild ways, which brings us onto the second group of galaxies: those that are radio-quiet. These are still active galaxies, but they aren't too bothered about kicking up a fuss in radio waves. Any jets that these comparatively laid-back active galaxies possess are both quite small and are almost a half-hearted attempt at their power.

Whether a galaxy is loud or quiet helps, in part, to identify these active galaxies even further. We've all heard the saying, or have been asked, to look



Our galaxy has great lobes spewing from the top and bottom of its disc. Discovered by the Fermi Gamma-ray Space Telescope, it's thought that this feature could point to a much more active past

at things from a different perspective. Astronomers take this literally when it comes to these bright, long-lived objects and seemingly, the angle that these energetic objects point at the Earth holds some relevance. "Precisely what is observed is very dependent on the viewing angle," explains Joanna Holt from Leiden University in the Netherlands. "If you look down [the centre of an active galaxy], you'll see more ultraviolet light and you will see emissions from what are known as the narrow and broad-line regions [narrow and broad wavelength bands across the electromagnetic spectrum]. If you look at an active galaxy edge-on, you will not see the broad-line region at all and the ultraviolet light you observe will not be directly from the galaxy's accretion disc, but the light that is scattered from particles outside a torus of dust that surrounds the accretion disc."

The model that Holt describes is called the unified model of active galactic nuclei. "The model consists of a central supermassive black hole, surrounded by an accretion disc that is then surrounded by a thick torus of obscuring material, shaped something like a doughnut," Holt explains. "All of this is embedded in a dense medium of clouds. The clouds that stray too close to the black hole, within the hole of the torus, are referred to as the broad-line region (BLR) and those that decide to hang back from the exotic object's appetite and rest outside the torus are dubbed the narrow-line region (NLR)."

It was American astronomer Carl Seyfert who realised in 1951 that several objects that he was observing around a lenticular galaxy (a cross between a spiral and elliptical galaxy) known as NGC 6027 seemed odd. Compared to other galactic structures he had seen, these objects had very bright star-like appearances. What's more, Seyfert reported that these objects seemed to have broader fingerprints – or emission lines – in their light spectrum. The astronomer thought that the latter piece of information was strange – all objects that he'd studied previously had shown a spectrum that didn't look too different to those made by stars. He'd found the active galaxies that we call Seyfert galaxies today and it was the first class of these highly energetic structures that had been found. As time has progressed, astronomers have also been able to break Seyfert galaxies into two groups – the Seyfert 1 and Seyfert 2 galaxies, which are distinguished by the angle that these galaxy types are viewed. These two are also known as radio galaxies.

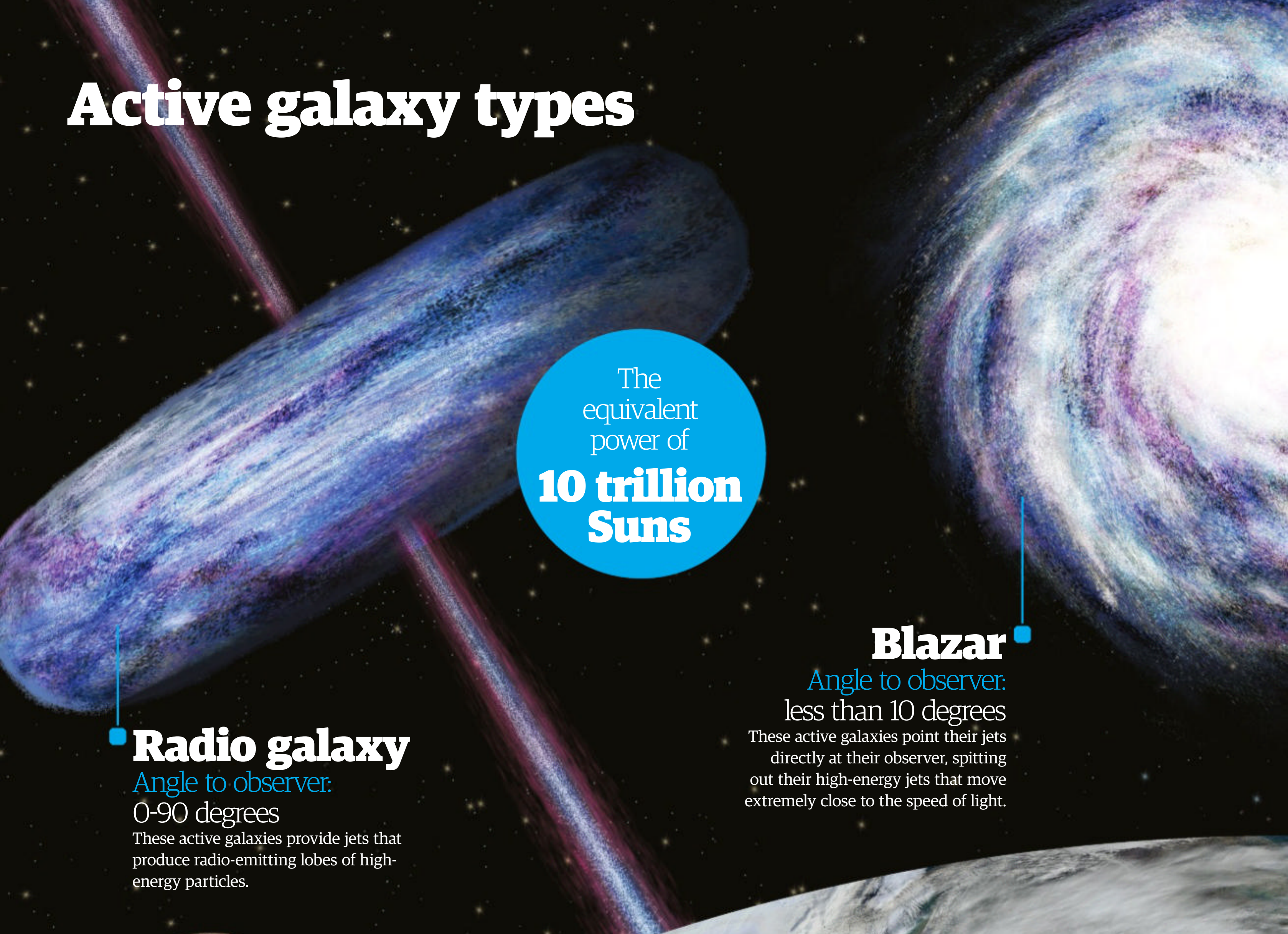
"If you look directly into the centre of an active galaxy you will see a Type 1 Seyfert galaxy," explains Holt. Since this type of galaxy has low optical luminosity, preferring to reveal themselves in the infrared, ultraviolet and X-ray bands, Seyferts belong to the radio-quiet family. Holt continues: "If the torus obscures the accretion disc, you will see a Type 2 Seyfert." As a result, any light that is thrown out from the so-called broad-line region is scattered by a halo of hot gas that surrounds the Seyfert's centre, allowing astronomers to grab an indirect view of what's going on.

However, it's when an active galaxy is angled in a substantial way to its observer, when things truly start to get interesting. "If we are looking within a few tens of degrees of the jet axis,

"Quasars are bright and so they are much easier to detect at great distances in the universe than normal galaxies"

**Joanna Holt, Leiden University**

# Active galaxy types



The equivalent power of **10 trillion Suns**

## Blazar

Angle to observer: less than 10 degrees

These active galaxies point their jets directly at their observer, spitting out their high-energy jets that move extremely close to the speed of light.

## Radio galaxy

Angle to observer: 0-90 degrees

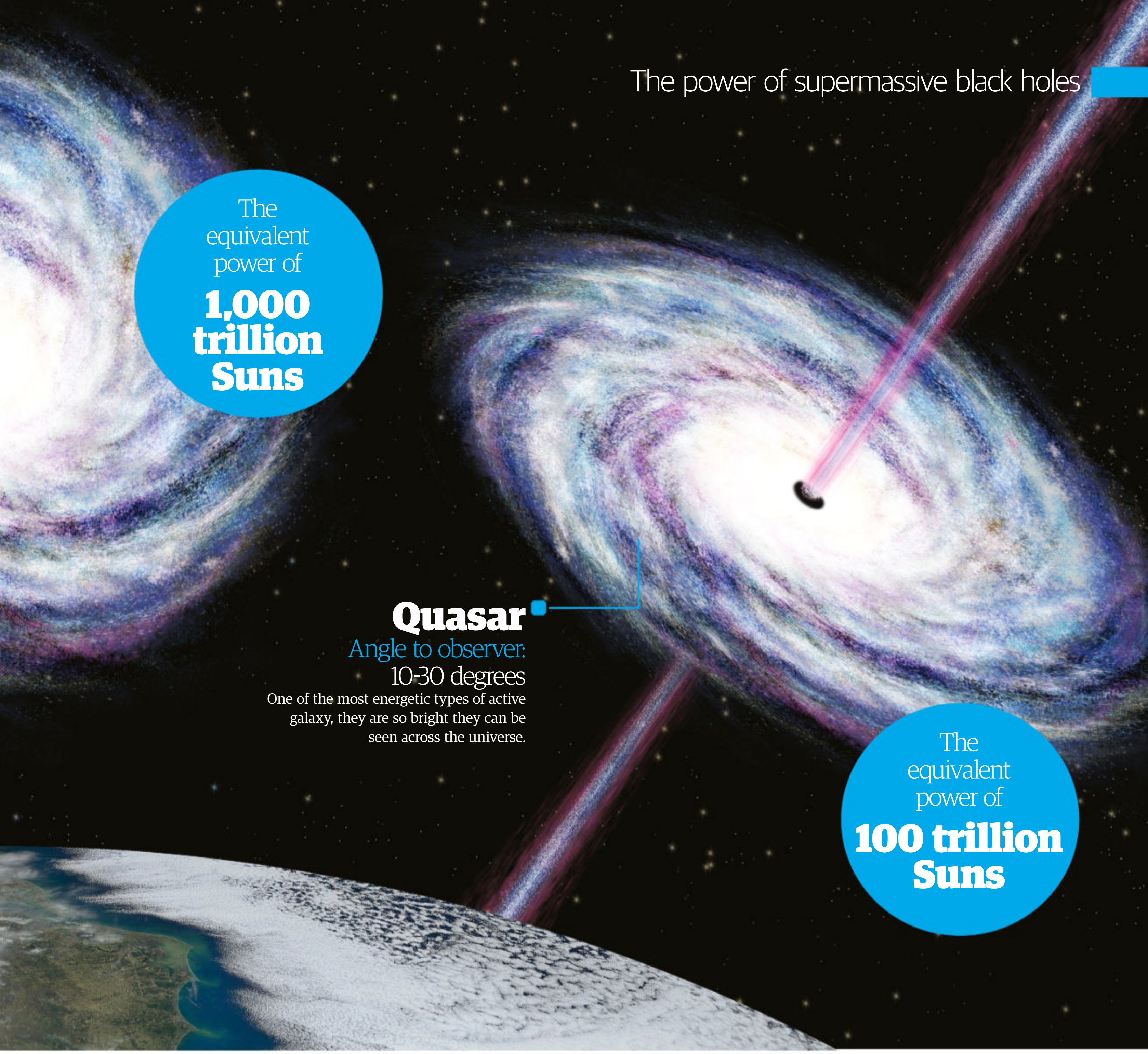
These active galaxies provide jets that produce radio-emitting lobes of high-energy particles.

we see more radiation that is beamed by the jets because they are travelling at a speed very close to that of light," says Marscher. "This causes the radiation to be beamed like a halogen flashlight in the direction of the jet outflow."

He is, of course, referring to the radio-loud quasars, distant dazzlers with centres that are around 1,000 times brighter than all of the host galaxy's stars put together. "Quasars are bright and so they are much easier to detect at great distances in the universe than normal galaxies," Holt adds. "They are rare but their numbers increase as you come across the less luminous type of active galaxy. Their numbers also increase when you look back to around 3 billion years after the Big Bang."

The quasar might be an attention-grabber but when it comes to overly intense galaxies, the blazar takes the crown - that's because when they're watched, the observer is in the line of fire. "In a blazar, the jet is pointing within several degrees of our line of sight, so the beaming is extreme," says Marscher. "Also, the jet is flowing towards us at up to 99.9 per cent of the speed of light, that means that events that occur in the jet are sped up and

> "In a blazar, the jet is pointing within several degrees of our line of sight, so the beaming is extreme"
>
> **Dr Alan Marscher, Institute for Astrophysical Research, Boston**



The equivalent power of **1,000 trillion Suns**

**Quasar**

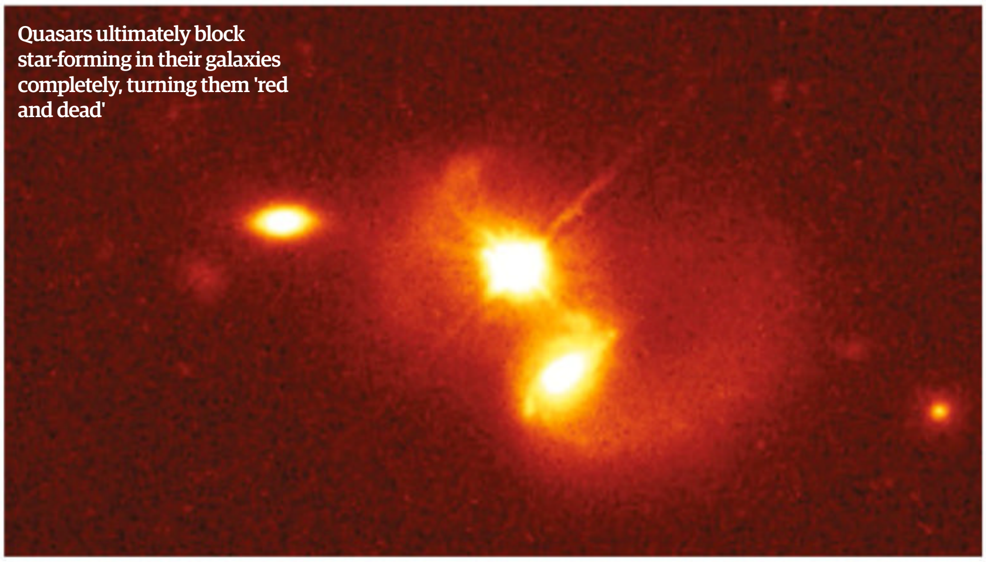
Angle to observer: 10-30 degrees

One of the most energetic types of active galaxy, they are so bright they can be seen across the universe.

The equivalent power of **100 trillion Suns**

take much less time to occur from our point of view." Furthermore, he says, the brightness we see is coming from within around ten light years of a black hole and noticeably changes on a time-scale as short as a matter of minutes. "We also see a bright microwave-emitting 'blob' moving at speeds that appear - just an illusion - to be faster than light."

Being the bearer of these exotic objects, active galaxies don't get off scot-free from the effects of the monstrous black holes within them. The intense radiation pouring out from them can heat the star-forming hydrogen gas in the galaxy, causing it to become too hot to form stars. If the galaxy is active enough, it can even blow this gas away, ejecting it from the galaxy. When this happens, star forming comes to an end in the galaxy and, over time, it becomes what astronomers call 'red and dead'. So quasars and blazars may shine the brightest over a short time, but in the long run they're doomed to die from the inside out.



**Quasars ultimately block star-forming in their galaxies completely, turning them 'red and dead'**

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# Are primordial black holes really giant gravitinos?

It's a long shot of an idea, but when it comes to the early universe, it's the best we've got

**Written by Paul Sutter**

Astronomers don't understand the origins of the biggest black holes in the universe. These black holes appear so early in the cosmological record that we might have to invoke new physics to explain their appearance.

New research proposes an intriguing origin story: the first black holes didn't come from stars but from clumps of super-exotic, super-hypothetical particles known as gravitinos that managed to survive the first chaotic years of the Big Bang.

## A little too super

There are black holes, and then there are big black holes. The largest black holes in the universe, appropriately named "supermassive black holes" (SMBHs), sit at the centres of almost every galaxy in the cosmos. Even the Milky Way has one, a monster at 4 million solar masses, designated as Sagittarius A*.

Giant black holes in the modern universe are a truly wondrous sight to behold, but in the past decade astronomers have revealed the existence of supermassive black holes at the very dawn of stars and galaxies, when the universe wasn't even a billion years old yet.

This is weird. It's weird because as far as we know, the only way to form black holes is through the deaths of massive stars. When they die, they leave behind a black hole a few times more massive than the Sun. To get to supergiant status, they have to merge with other black holes and/or consume as much gas as possible, bulking up all those millions of solar masses.

And that takes time. A lot of time. In the early universe, stars themselves took hundreds of millions of years to first appear. And as far as we can tell, right alongside that first generation of stars and galaxies were supermassive black holes. There doesn't appear to have been enough time for those giant black holes to form through the usual and customary stellar death route, so something fishy is up.

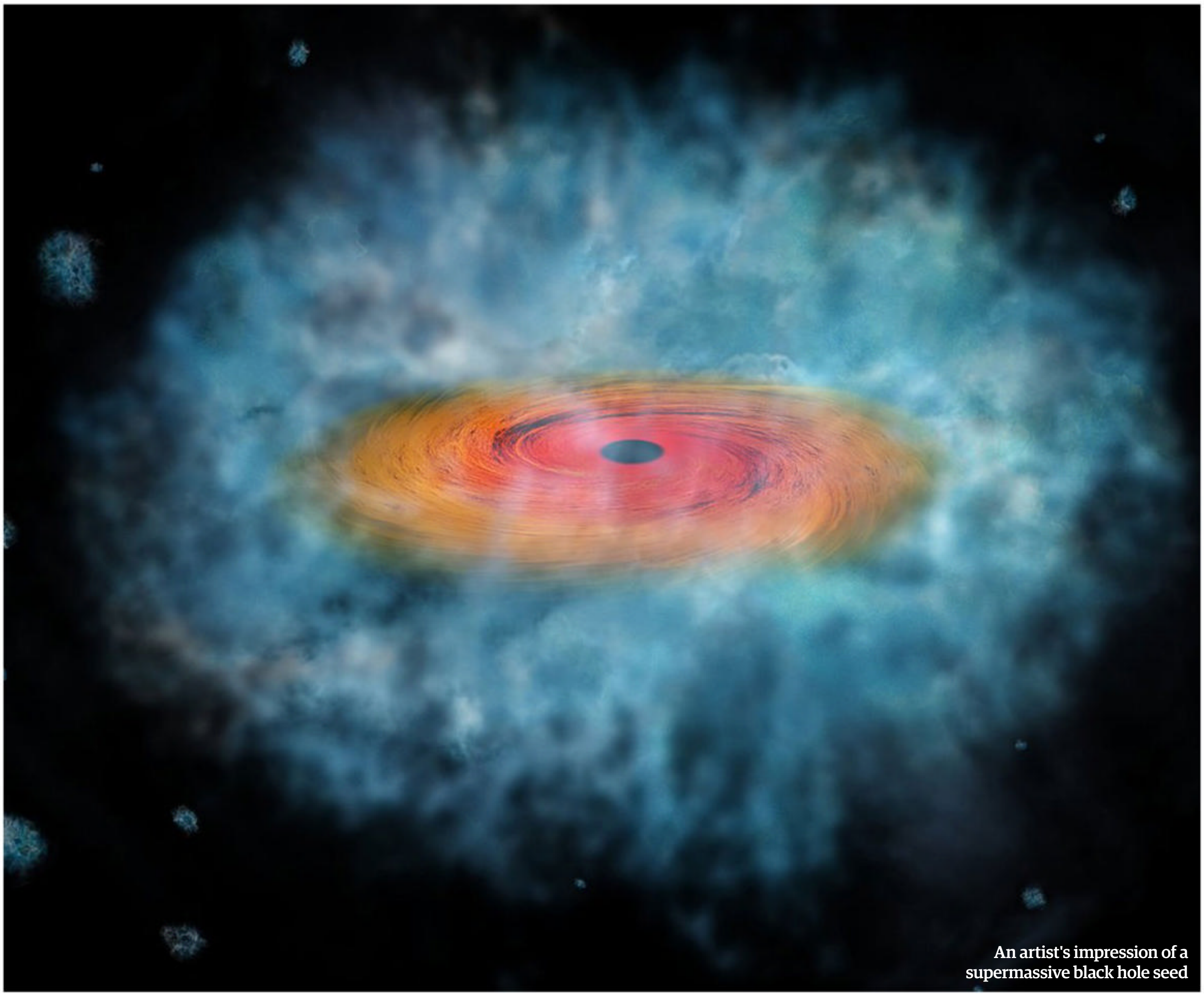
Either we don't understand something fundamental about the astrophysics of black hole growth (which is perfectly possible), or the first, giant black holes actually formed in a much earlier, much more primordial epoch. But in order for that to happen, the physics that created those possible first black holes has to be… weird.

> "Can one have atoms in which the nucleus is a tiny primordial black hole, formed in the early universe?"
>
> **Stephen Hawking**

## Gravity's twin

How weird? Well, so weird that it goes far, far beyond the current boundaries of known physics. Thankfully, theoretical physicists are hard at work, every single day, to go far, far beyond the current boundaries of known physics. One such example is called supersymmetry, and it's an attempt by physicists to both explain some of the inner workings of the particle world and to predict the existence of brand-new particles.

Primordial black holes date back to the early days of the universe



An artist's impression of a supermassive black hole seed

NASA/CXC/M. Weiss

In supersymmetry, every particle of the Standard Model (the name given to our current best understanding of the subatomic realm) is paired with a partner. The reason for this pairing is a fundamental symmetry found deep in the mathematics that might describe nature.

But this symmetry is broken (through the machinations of some complex mechanisms), so the supersymmetry partner particles don't simply float around in the world or make grand entrances in our particle colliders.

Instead, because of the broken symmetry, the partner particles are forced to have incredible masses, so high that they can only appear in the highest-energy reactions in the universe. So far, we haven't found any evidence for supersymmetry partner particles in our collider experiments, but we're still looking.

While the search goes on, theorists spend their time toying around with the various models and possibilities of supersymmetry. And in one version, there's a particle known as the gravitino. The gravitino is the supersymmetry partner particle of the graviton, which itself is the hypothetical particle that carries the force of gravity.

If you're starting to worry that all this sounds a bit too hypothetical, it's okay. The existence of the gravitino is highly speculative and not based on any existing evidence. But, as we will soon see, some models of the gravitino imbue them with some very special properties that make them ripe for seeding the formation of black holes.

## Running the gauntlet

If you want to make some black holes in the early universe, you have to pass a few challenges. Well before the first stars and galaxies appeared, our universe was dominated by radiation: high-energy light flooded the cosmos, bossing around the matter and generally telling everyone what to do.

If you want to create some random black holes in that radiation-dominated epoch, you have to do it fast, because that era in our universe was extremely chaotic. And once you form the black holes, you have to keep them alive. Black holes evaporate through a quantum mechanical process known as Hawking radiation, and small black holes (say, ones formed through some exotic subatomic process) can quickly disappear before they get a chance at greatness, let alone supermassiveness.

Enter the gravitino, or at least one version of that hypothetical particle. According to a research article recently published to the preprint journal arXiv, the high-energy early universe could have had just the right conditions to populate the universe with gravitinos. Because of their unique properties (most notably, their ability to quickly gravitationally attract each other), they could quickly form microscopic black holes.

As time goes on in the early universe, the black holes could grow large enough that they could feast on the surrounding radiation before succumbing to Hawking evaporation. Once the radiation cleared away, they could be big enough to continue collecting matter through normal astrophysical processes, providing the seeds for the first giant black holes.

It's a long shot of an idea, but when it comes to the early universe, it's the best we've got.

## 5 AMAZING FACTS ABOUT

# Double black holes

### They're made in galaxy collisions

It's common belief that galaxies each have a supermassive black hole nestled at their centres, but what happens to them when one galaxy is on a collision course with another? It turns out that these monstrously hungry and hefty objects have the opportunity to share the same galactic centre, roughly separated by tens of light years at most.

### They spew strong gravitational waves

Double black holes are thought to be the strongest source of elusive gravitational waves. This radiation ripples through the fabric of space-time, taking the form of waves, which have never been observed directly. They're made when one of the duo spirals towards the other, when the pair's orbit has decayed, eventually combining as one.

### Their event horizons make duckbill shapes

What becomes of a black hole's event horizon - the point of no return - when two of these exotic objects get close? Scientists think that as they approach, their event horizons protrude as duckbill shapes towards each other, extending longer and narrower.

### They move at incredible speed

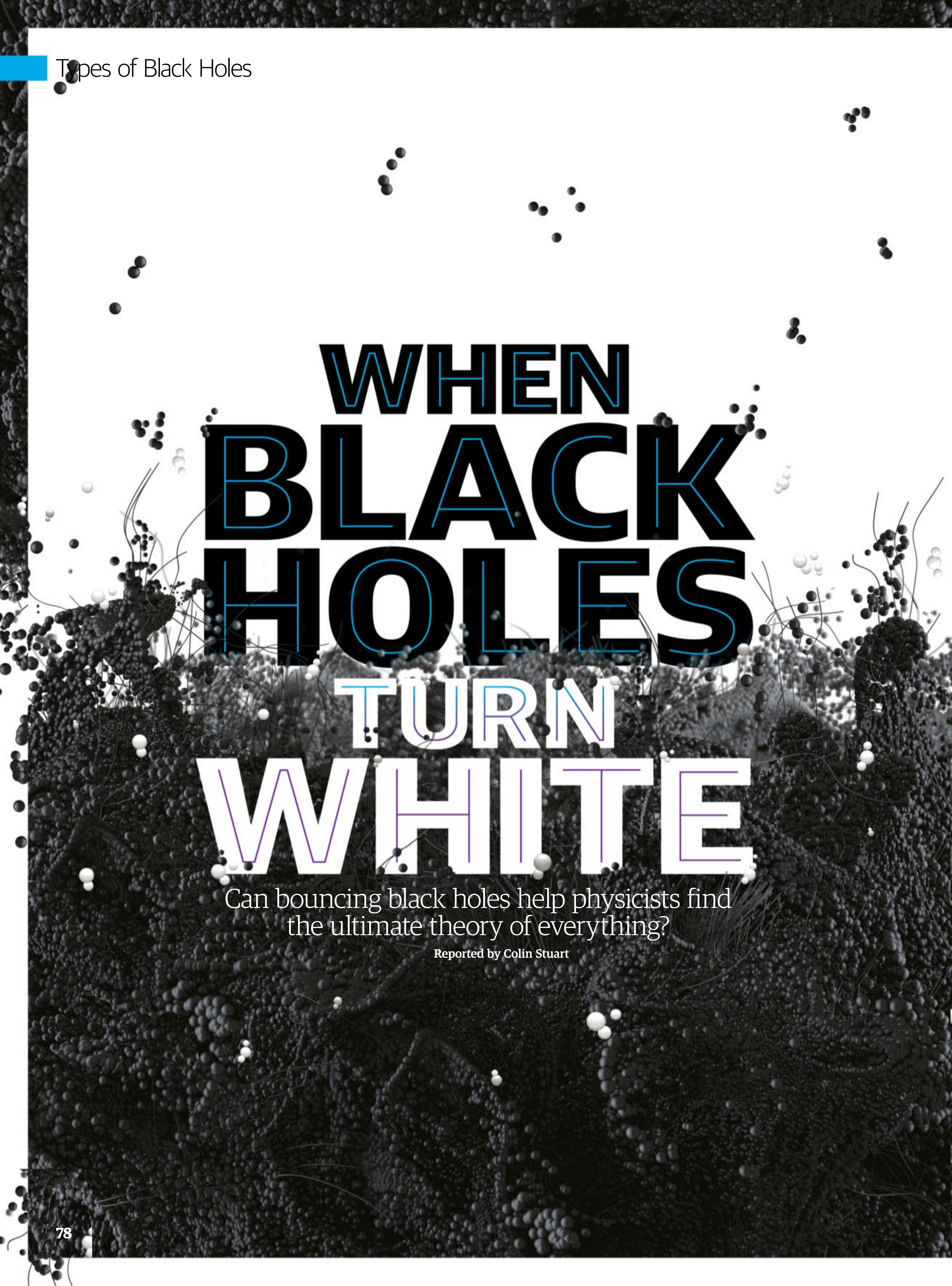
Despite their masses, supermassive black holes are not sluggish by any means. Astronomers are able to figure out - with the help of the Doppler shift - that binary supermassive black holes should generally orbit each other at speeds of around 3,800 kilometres per second - that's 8.5 million miles per hour.

### Not many have been found

It's certainly no secret that binary black holes are hard to come by, despite the universe being littered with galactic smash-ups. Astronomers think that over 30 examples probably exist but have only pegged a few including one in the double nucleus of NGC 6240, which is the remnant of a merger between two smaller galaxies.

Only a handful of these incredible cosmic collisions have been found

© Jay Wong



# WHEN BLACK HOLES TURN WHITE

Can bouncing black holes help physicists find the ultimate theory of everything?

**Reported by Colin Stuart**

Somewhere out there in the vastness of space lurks a black hole smaller than the full stop at the end of this sentence. Minuscule but mighty, it could hold the key to unlocking some of the greatest mysteries in the universe.

Black holes are the ultimate cosmic laboratory, a way for physicists to test out their theories in an environment so extreme that space and time are curved and warped. Even light cannot resist their eternal grasp, so we see no light reflected from them at all. We can only spot them when their gravity affects something visible or they merge to create gravitational waves. Few places have such a high amount of energy in such a small space.

But what happens if you fall into one? The bad news is you're unlikely to survive the ordeal. The difference in gravity between your feet and your head would eventually get so extreme that it would overcome the forces holding your atoms together. You'd be torn apart into thin strips of human spaghetti, which is where the process gets its whimsical name: spaghettification. Where do your spaghettified atoms ultimately end up? What's at the bottom of a black hole?

**What is a white hole?**
**Black holes are places where you can go in and you can never escape, while a white hole is a place where you can leave but can never go back.**

© Alper Durmaz

Our best answer currently comes from our leading theory of gravity: Einstein's General Theory of Relativity. It tells us that a singularity awaits - an infinitely small, infinitely dense point where space and time cease to be. Hit it and you're immediately erased from existence. Yet if you crush something down much smaller than an atom you enter the arena of quantum physics. At the moment we're yet to take its weird and wonderful rules into account at the bottom of black holes because we have no way of combining it with general relativity. The search for such a theory of 'quantum gravity' is the ultimate goal for many physicists. A Nobel Prize would surely be in the offing for anyone who finds one that accurately describes our universe. It might also help us explain where our cosmos came from because, according to general relativity, the other place you find a singularity is at the moment of creation - the Big Bang - where time and space sprang into existence.

Carlo Rovelli, director of the quantum gravity group at Aix-Marseille University in France, doesn't believe in singularities. "You cannot compress things too much," he says. "It is a universal thing in nature." He argues we need quantum gravity to help explain what happens instead. Rovelli is a founder of one approach to this thorny problem of getting the two theories to play nicely together: loop quantum gravity (LQG). According to Einstein, the fabric of space-time is smooth. However, proponents of LQG suggest that it isn't. "That's not surprising," says Rovelli. "Other things in the universe like light and the energy of electrons come in chunks." He suggests space is not smooth, but grainy - it's also made of tiny little chunks or loops. Think of it like a piece of cloth; at first glance it may seem smooth, but look at it under a microscope and you'll see that it's really made of a series of stitches.

If you apply this logic to the depths of a black hole you get a remarkable result. Occasionally a black hole might 'bounce' into its polar opposite: a white hole. "With a black hole you get sucked in, but with a white hole things can only come out," says Francesca Vidotto from Radboud University in The Netherlands.

What exactly triggers the change? According to Vidotto it is simple chance. Quantum physics is defined by probability. You can never say exactly where an object is or what state it is in, only where it is more likely to be when you make a measurement. But the smaller an object, the more likely it is for unusual things to happen. Vidotto says an object has a timescale over which it can display these weird quantum properties. "For large objects, like a person or a cat, this time is much larger than the age of the universe," she says. "For a planet-sized black hole it is about the age of the universe." But for a black hole just half a millimetre across you'd expect it to have happened fairly often already across the cosmos. We normally think of black holes as much bigger than that - formed by the deaths of the most massive stars. However, astronomers also imagine there may be primordial black holes out there. Tiny ones formed in the early universe shortly after the Big Bang. Some of those could now be making this odd transition into a white hole.

### Eternal black hole theory

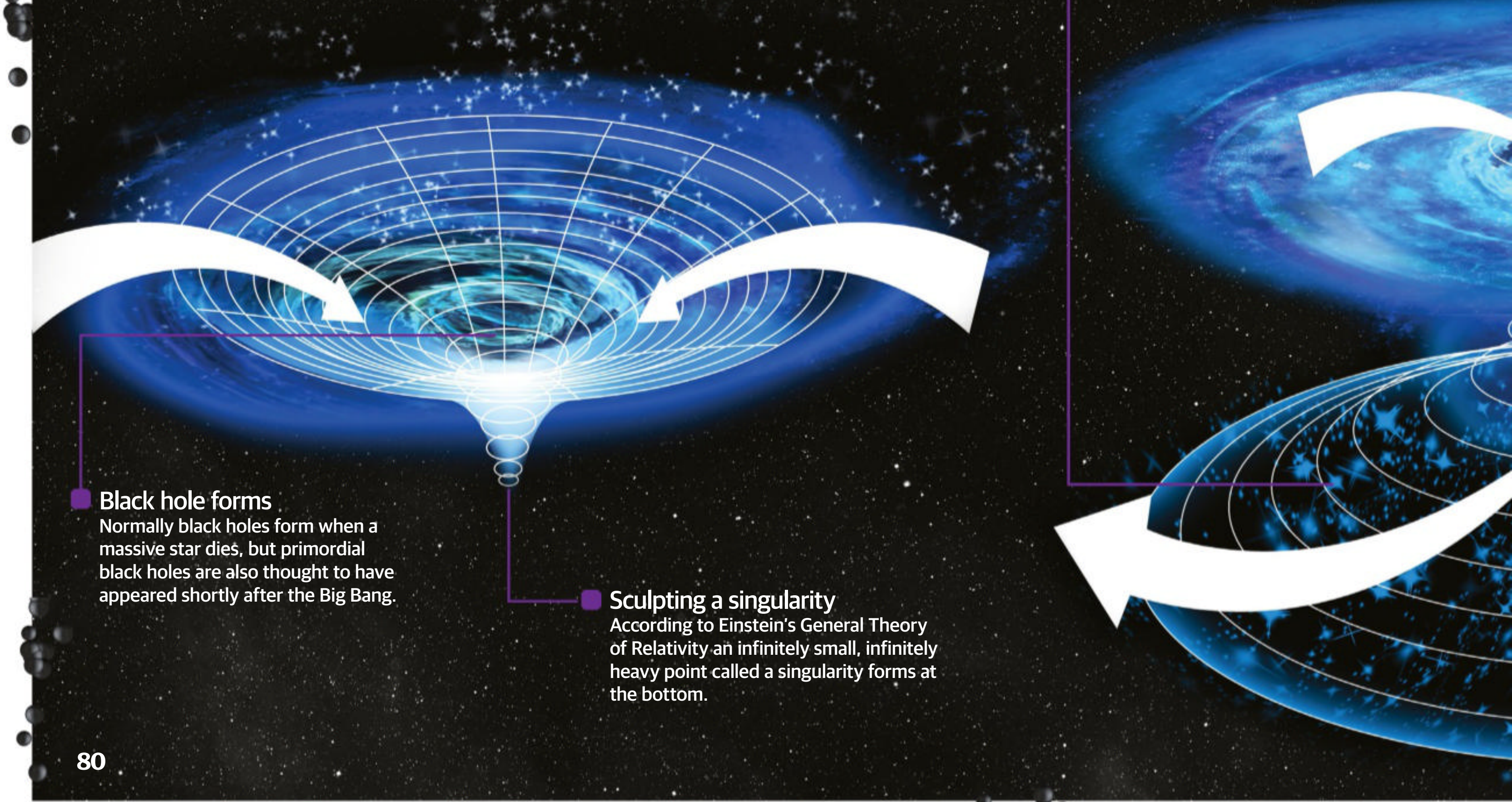
White holes belong in the theory of eternal black holes: interesting concepts that widely assume that matter that enters a black hole is permanently lost and past the point of no return.

> "With a black hole you get sucked in, but with a white hole things can only come out" **Francesca Vidotto**

If that's true we should be able to see evidence of it happening with our telescopes. "You would expect an explosion," says Vidotto. Such a detonation would trigger the rapid release of huge

## Meet the white hole

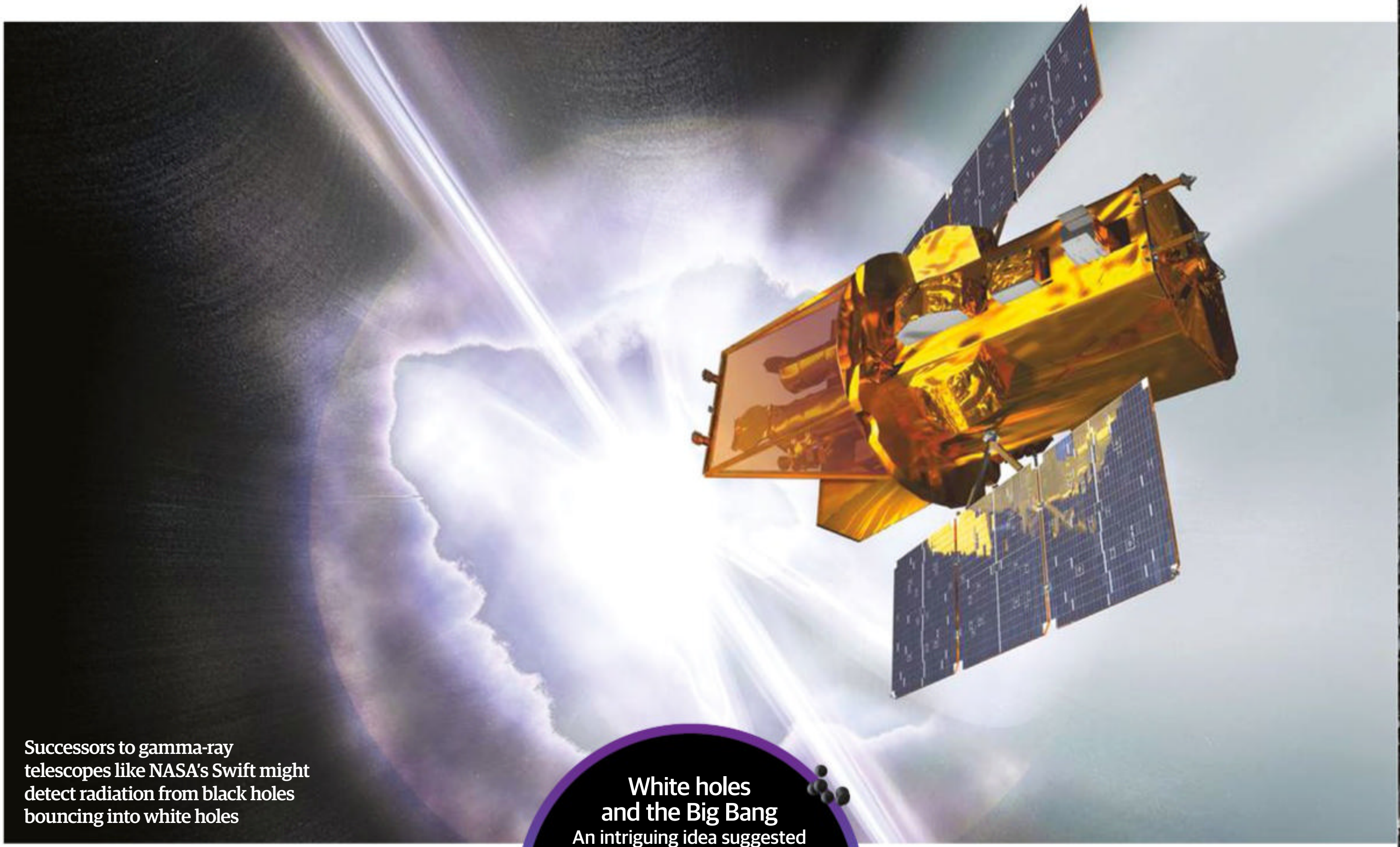
What do we know about these mysterious objects?



**Black hole forms**
Normally black holes form when a massive star dies, but primordial black holes are also thought to have appeared shortly after the Big Bang.

**Sculpting a singularity**
According to Einstein's General Theory of Relativity an infinitely small, infinitely heavy point called a singularity forms at the bottom.

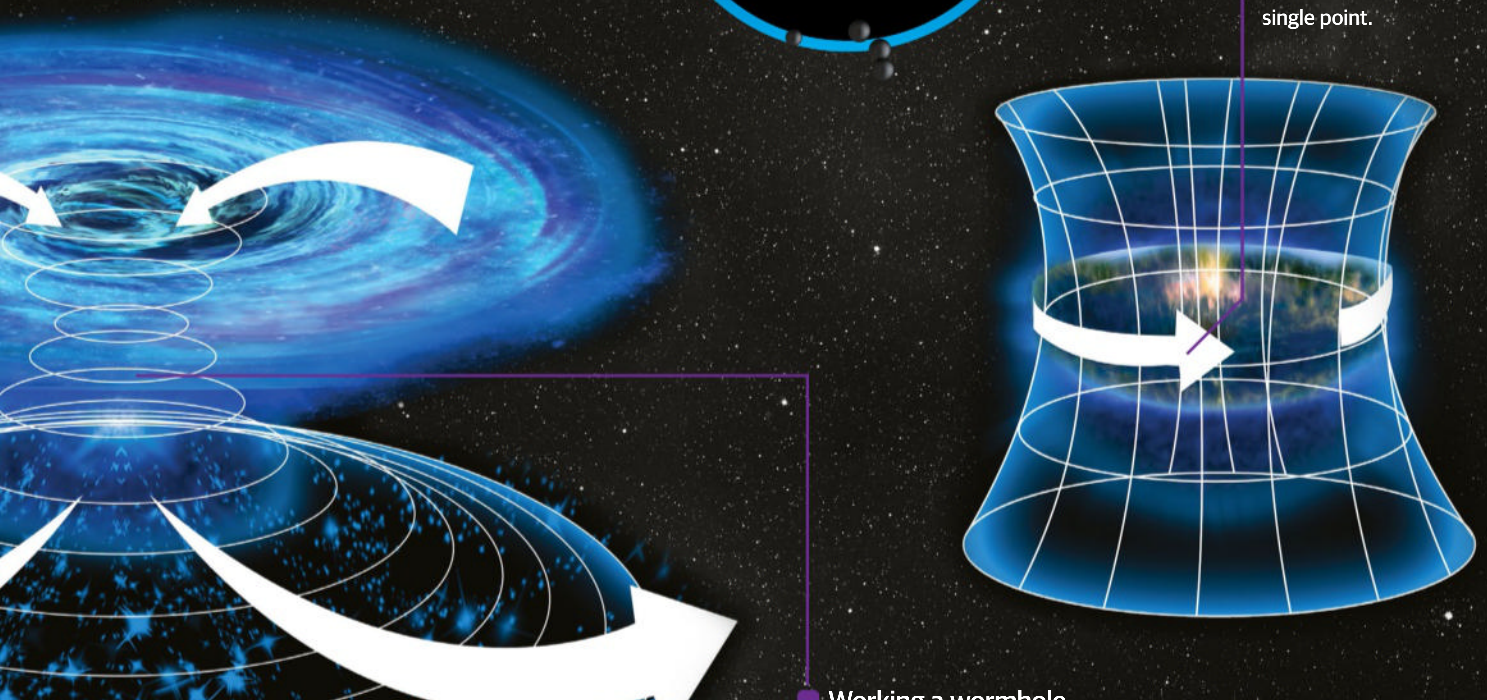
**Pushed into the past**
You are eventually spat out of a white hole - an object you can never return through - to emerge in the past (or another universe).



Successors to gamma-ray telescopes like NASA's Swift might detect radiation from black holes bouncing into white holes

### White holes and the Big Bang

An intriguing idea suggested by cosmologists implies that a 'matter-spewing' white hole could be the reason behind the birth of the universe, which we believe was brought about by an event about 13.8 billion years ago known as the Big Bang.



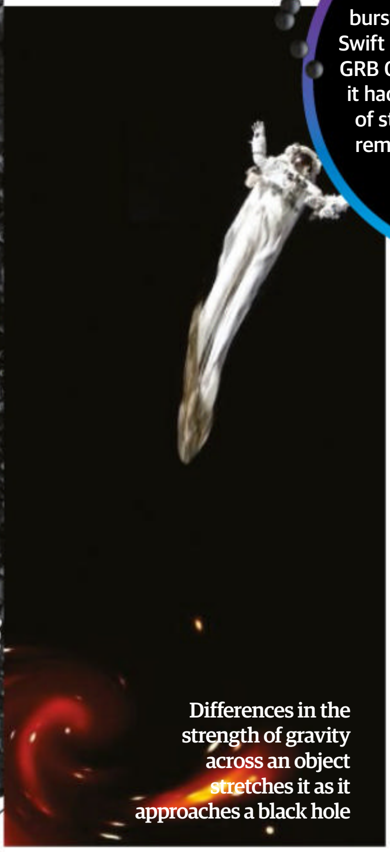
**Spinning singularities**
A rotating black hole would form a ring-shaped singularity with a hole in the middle rather than a single point.

**Working a wormhole**
A bridge opens up between the present and the past known as an Einstein-Rosen bridge or, more colloquially, a wormhole.

© Nicholas Forder

### White hole candidate

A powerful gamma-ray burst was picked up by NASA's Swift satellite in 2006. Known as GRB 060614, the burst was odd; it hadn't taken place in a region of star formation and lasted a remarkable 102 seconds. Had astronomers found a candidate?



Differences in the strength of gravity across an object stretches it as it approaches a black hole

amounts of energy. How energetic this radiation is depends on the size of the black hole. For black holes the size of your hand or smaller you'd expect it to be the radio part of the spectrum. And over the last decade astronomers have found a handful of unexplained events that might just fit the bill: fast radio bursts (FRBs).

The first was spotted in 2007 and, while there are still many mysteries surrounding them, it is clear they are coming from beyond our galaxy. The nearest emanated from over a billion light years away. Some astronomers have even suggested they might be attempts by aliens to get in contact. Far more likely is that they have some astronomical origin, but what exactly? Perhaps they are generated by colliding black holes or neutron stars. However, there is a way we might be able to prove once and for all that they really are coming from black holes bouncing into white holes.

According to calculations by Rovelli and Vidotto, more distant bursts should have more energy than those nearby. That's because black holes are thought to evaporate over time by releasing Hawking radiation, named after the late physicist Stephen Hawking. Younger black holes in the distant universe should therefore be bigger and release more energy than older black holes closer to us that have had more time to evaporate.

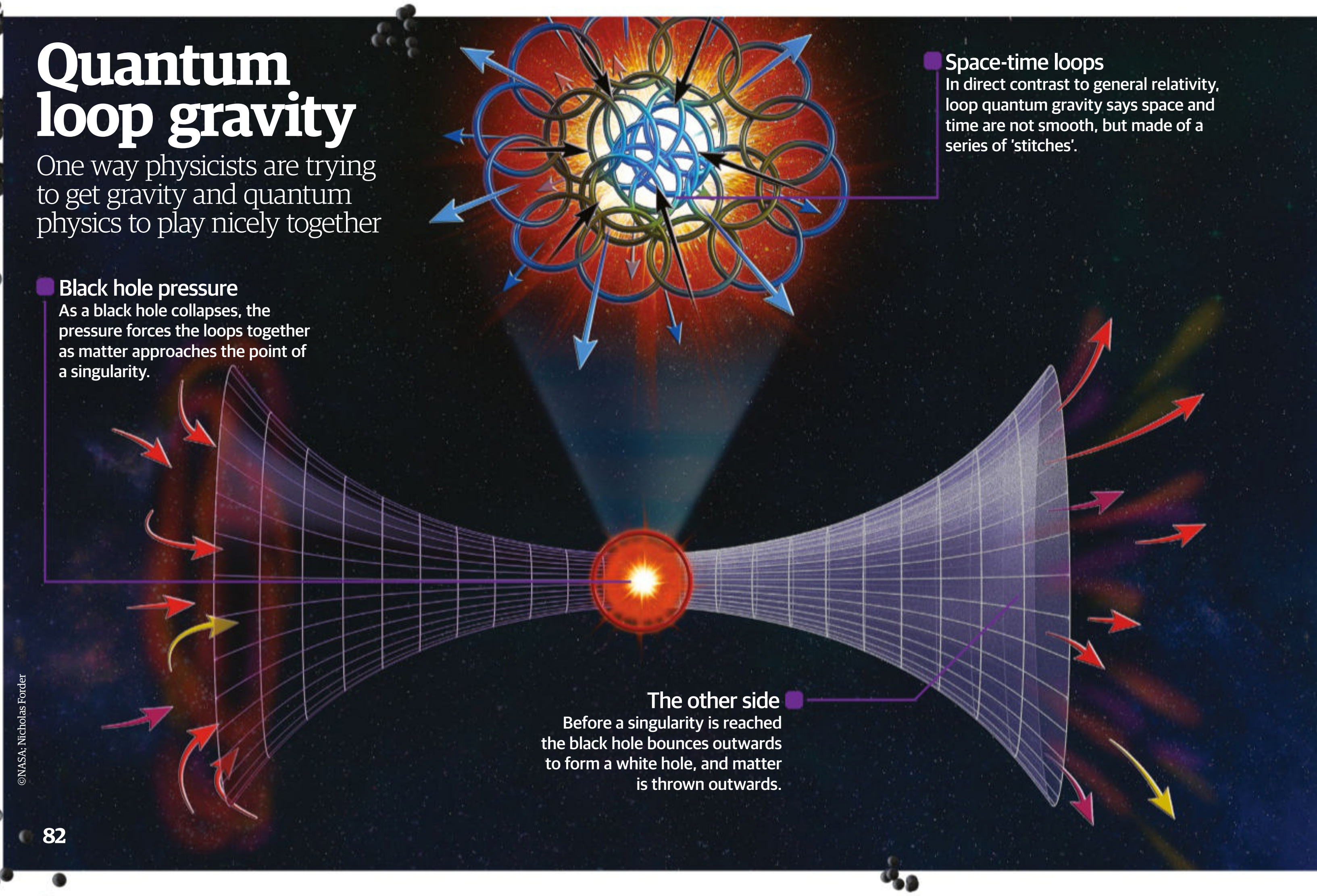
This is in direct contrast to the way things normally work in astronomy. As the universe expands it dilutes the amount of energy in a given amount of space. There's more space between us and a distant object to stretch, so far-away objects have their energy watered down more than those close to us. With bouncing black holes you'd expect the two effects to cancel each other out, meaning these explosive events would have a similar energy across a wide range of cosmic distances. According to Vidotto, observing this behaviour "would be a smoking gun for our theory".

There are some potential snags, however. The FRBs discovered so far are not of the exact energy you would expect from a black hole to white hole bounce. That may not be the end of the world according to Hal Haggard from Bard College in New York. "Given how imprecise the calculations are it's not surprising," he says. "It's in the right ball park." More concerning is that astronomers have identified a repeating fast radio burst called FRB 121102. First discovered in 2012, more than 15 distinct pulses are associated with the same source. "There's nothing in the white hole theory that calls for that," says Haggard. "If more and more of these repeating bursts are found then that goes against this proposal."

He believes the white hole interpretation is extremely speculative, but the pay-off is potentially huge. "It's exciting because there are so few ways

## Quantum loop gravity

One way physicists are trying to get gravity and quantum physics to play nicely together



**Space-time loops**
In direct contrast to general relativity, loop quantum gravity says space and time are not smooth, but made of a series of 'stitches'.

**Black hole pressure**
As a black hole collapses, the pressure forces the loops together as matter approaches the point of a singularity.

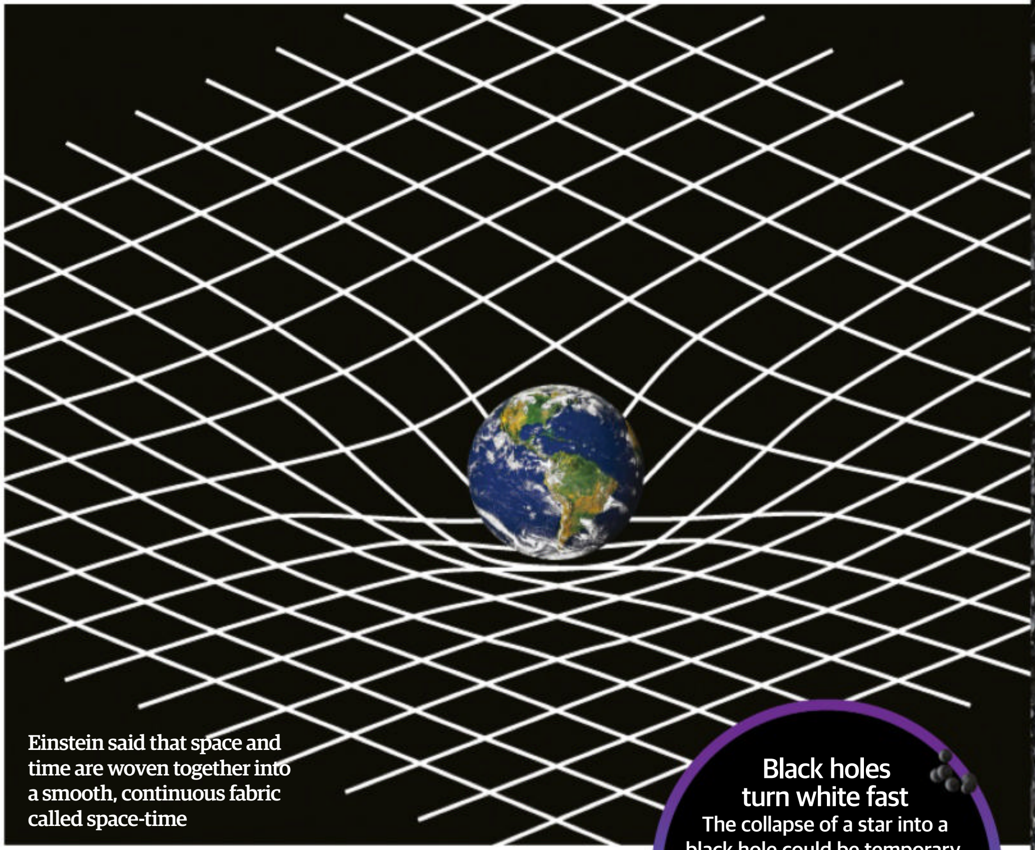
**The other side**
Before a singularity is reached the black hole bounces outwards to form a white hole, and matter is thrown outwards.

©NASA; Nicholas Forder

to test quantum gravity currently on the table." But confirming a black to white hole transition wouldn't immediately crown loop quantum gravity the victor. Haggard says the approach taken so far is "a generic model that doesn't leverage anything specific about the theory of quantum gravity you're using". However, further detailed observations of how the explosions played out could do the trick. "Detailed analysis of the signals would be able to distinguish between theories, and that's why this is so exciting," says Haggard.

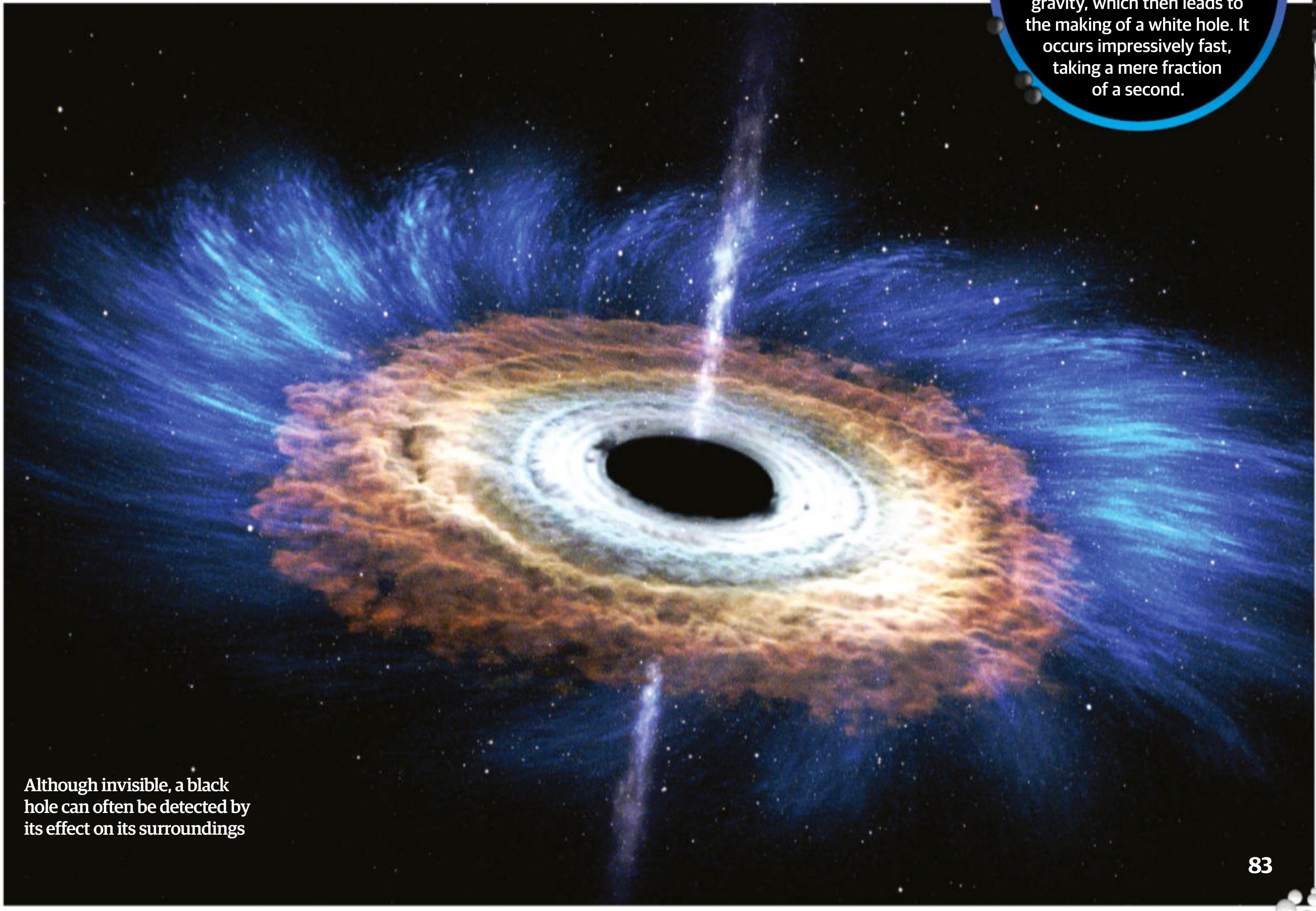
Given the high stakes, fortunately there are other ways a black hole to white hole bounce could show itself. According to Vidotto the explosive event should also generate gamma rays – the highest energy part of the electromagnetic spectrum. Although we do already have gamma-ray telescopes in space peering into the universe, Vidotto says "they are not yet optimised to see in

> "It's exciting because there are so few ways to test quantum gravity currently" **Hal Haggard**


Einstein said that space and time are woven together into a smooth, continuous fabric called space-time

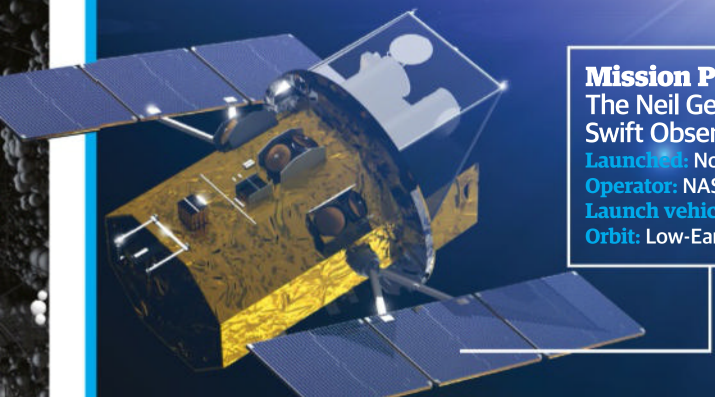
**Black holes turn white fast**

The collapse of a star into a black hole could be temporary, according to loop quantum gravity, which then leads to the making of a white hole. It occurs impressively fast, taking a mere fraction of a second.


Although invisible, a black hole can often be detected by its effect on its surroundings

# Have we already discovered one?

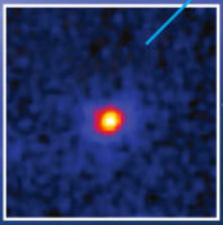
A gamma-ray burst from 2006 could be our first sighting



**Mission Profile:**
The Neil Gehrels Swift Observatory
**Launched:** November 2004
**Operator:** NASA
**Launch vehicle:** Delta 7320
**Orbit:** Low-Earth

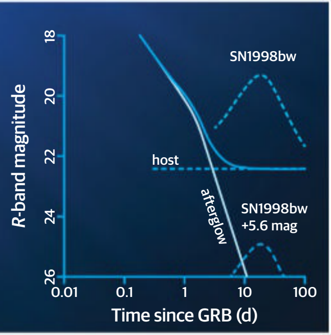
### A possible white hole?

Back in June 2006, the Swift satellite captured a burst of gamma rays. Since no supernova was seen following the event, astronomers realised that they had come across a possible new object. In 2011 it was hypothesised that the burst was a white hole.



### Possible origins

GRB 060614 has behaviours of both long and short bursts, leaving astronomers to believe that its birth occurred unusually. The burst sits in a galaxy with very few stars that could produce either an exploding star or a long burst.



> “What is remarkable is that no new physics is needed. No strings, no new forces and no new particles” **Carlo Rovelli**

such high-energy gamma rays”. Future gamma-ray observatories may well be up to the task, however. In the meantime there’s a third way in: synchrotron emission. Particles like electrons would be accelerated through strong magnetic fields during the high-energy explosion, emitting radiation as they do so. “The challenge is how can we distinguish these cosmic rays from all the other sources in the sky,” says Vidotto.

If any one of these endeavours is ultimately successful, confirming a black hole to white hole transition won’t just help with the mystery of quantum gravity. It could also tackle an equally perplexing puzzle currently frustrating astronomers: dark matter. When we look at galaxies and clusters of galaxies there appears to be far more gravity than can be accounted for using visible material like stars and gas alone. Instead astronomers have suggested there is some hidden material skulking in the shadows which acts like a galactic glue, helping bind galaxies together with its own gravitational pull. The most fashionable contender for this dark matter has been supersymmetry – the idea that alongside the familiar sub-atomic particles like electrons and protons there are bigger particles that are their mirror images. The lightest of these supersymmetric particles has been the go-to explanation for dark matter for well over a decade. Despite a lot of searching, no one has ever found a supersymmetric particle.

That’s causing some physicists to look elsewhere for an explanation. Rovelli believes the remnants left behind as a black hole transitions into a white hole could go some way to providing the missing gravity. Being so small, they would be hard to detect other than by their collective gravitational pull. “What is remarkable is that no new physics is needed. No strings, no new forces and no new particles,” Rovelli says, referring to string theory – an alternative way to attack the problem of quantum gravity. Haggard agrees it’s possible that “they could make up a substantial fraction of dark matter”. He also says that “dark matter may not be one thing – it may be a mixture of particles we haven’t discovered and something else”. That something else could be black holes turning white.

### Secret ingredient to dark matter

According to recent research, these black hole opposites could constitute dark matter, the mysterious substance that forms a decent proportion of matter in the universe.

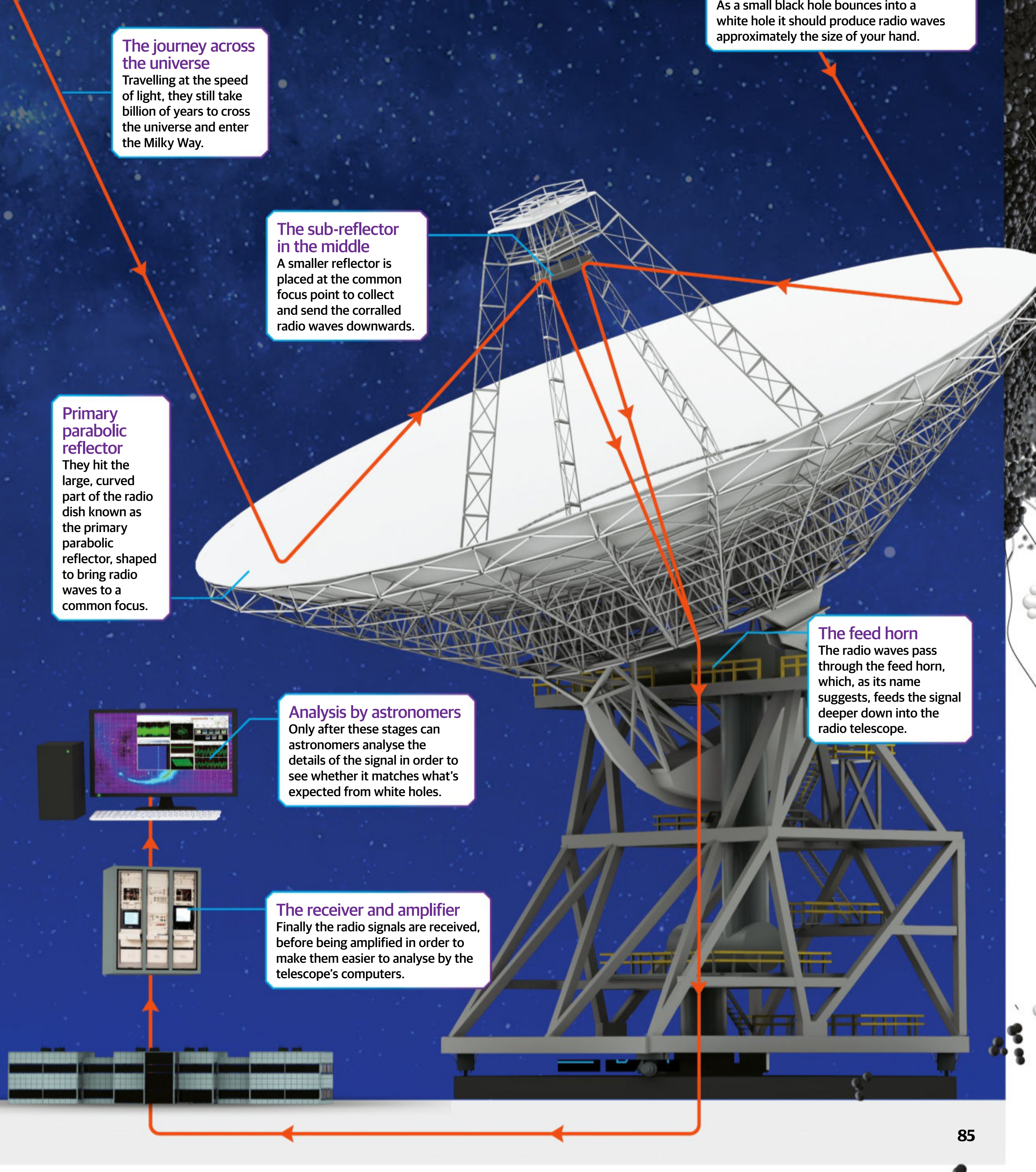
For now astronomers are left in a tantalising position. Through fast radio bursts we might not only have the first clues that black holes can morph into their polar opposites, but also a way to tackle the ultimate questions about the nature of space and time itself. Then again, we may not. Only more observations with more telescopes from one end of the electromagnetic spectrum to other will tell us whether to call the Nobel committee or return to the drawing board. The stakes couldn’t be higher.

Could dark matter be made up of black holes?

©Adrian Mann;

# Our hunt for the white hole

How might an 'inverse black hole' show itself to our telescopes?



### Radio waves created by white hole

As a small black hole bounces into a white hole it should produce radio waves approximately the size of your hand.

### The journey across the universe

Travelling at the speed of light, they still take billion of years to cross the universe and enter the Milky Way.

### Primary parabolic reflector

They hit the large, curved part of the radio dish known as the primary parabolic reflector, shaped to bring radio waves to a common focus.

### The sub-reflector in the middle

A smaller reflector is placed at the common focus point to collect and send the corralled radio waves downwards.

### The feed horn

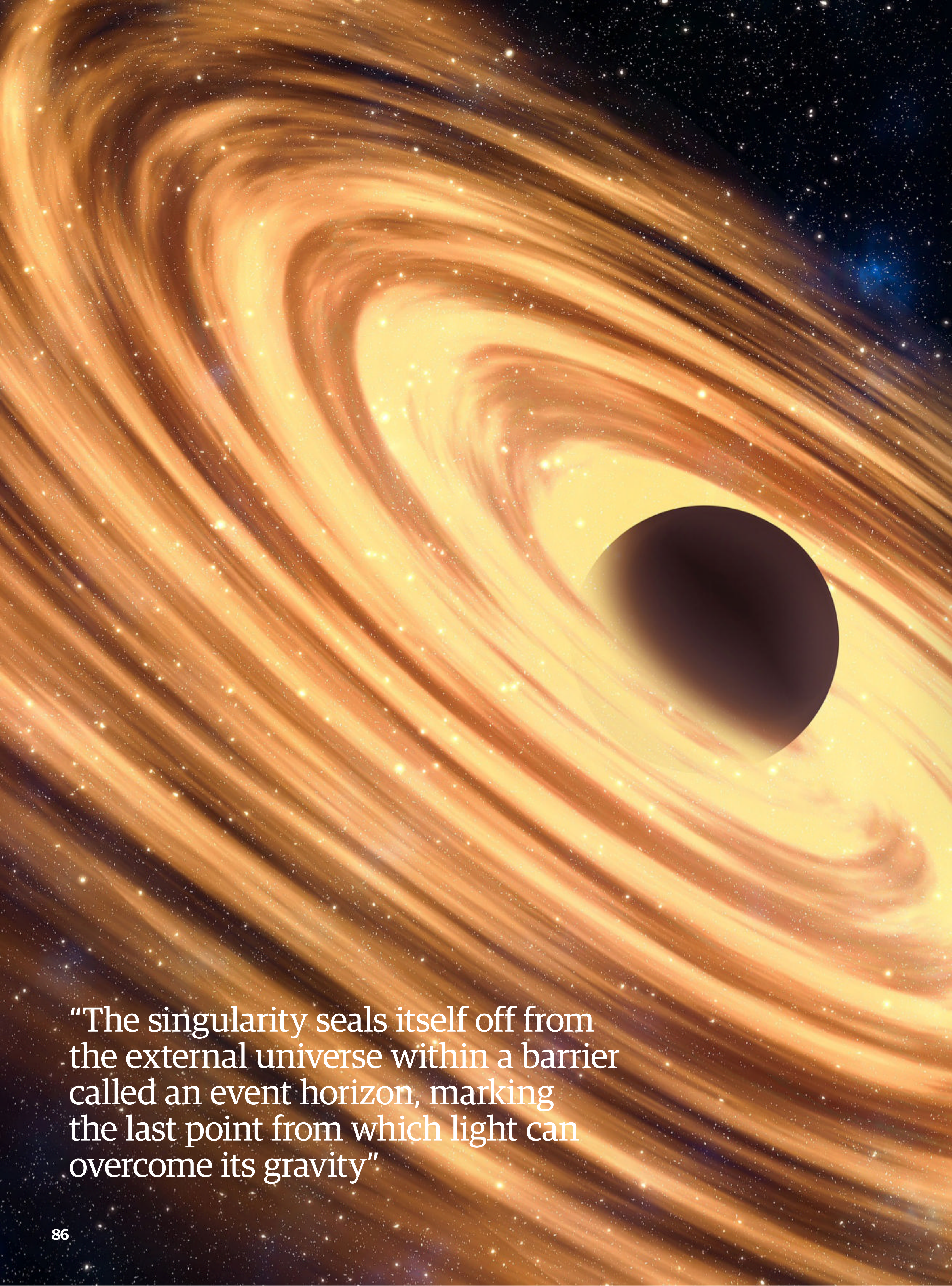
The radio waves pass through the feed horn, which, as its name suggests, feeds the signal deeper down into the radio telescope.

### The receiver and amplifier

Finally the radio signals are received, before being amplified in order to make them easier to analyse by the telescope's computers.

### Analysis by astronomers

Only after these stages can astronomers analyse the details of the signal in order to see whether it matches what's expected from white holes.



“The singularity seals itself off from the external universe within a barrier called an event horizon, marking the last point from which light can overcome its gravity”

# Finding Black Holes

## Answering some of the important questions in the hunt for black holes

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# Peering into the heart of a BLACK HOLE

Detecting a black hole isn't hard, but taking a picture of one is almost impossible. That is, until astronomers set up the Event Horizon Telescope to peer into the unknown

Written by Luis Villazon

In April 2017, more than 1,000 computer hard disks were air freighted from seven observatories on three continents to data processing centres in the United States. Between them, these disks carried more than three petabytes of data. That's more than you would need to store every Hollywood movie ever made, including all the DVD bonus features. But it will be barely enough to create a single blurry image of one of the most elusive objects in the universe: a black hole. The data for this tiny snapshot comes from a telescope almost the size of the planet - the Event Horizon Telescope, or EHT for short.

Black holes come in two main varieties. Stellar black holes form when a large star runs out of fuel and explodes as a supernova, blasting away its outer layers and collapsing in on itself under its own weight until it has zero volume and forms a singularity in space-time. Because they blast away most of their initial mass when they explode, even very large stars can end up as relatively small black holes. The largest stellar black hole we know of is about 30 times the mass of the Sun and the smallest is just 4-10 times the mass. But there is another distinct class of black hole called the supermassive black hole.

There is still some debate about how these objects form, but according to Professor Fulvio Melia of the Steward Observatory at the University of Arizona, it's possible that they are just older. "Supermassive black holes had much more time to grow, since their seeds were presumably formed around 400-600 million years after the Big Bang. But to grow to their current size, they had to have been suitably placed in regions with a lot of gas to accrete, in other words in the nucleus of galaxies." This head start means that supermassive black holes can be many millions of times more massive than a stellar black hole. The supermassive black hole at the centre of our galaxy, called Sagittarius A*, is more than 4 million times the mass of the Sun, for example.

Despite its huge size, no one has ever directly imaged Sagittarius A* through a telescope, and that is not because black holes are invisible. Despite their name, black holes cause the expulsion of enormous amounts of radiation. Of course, nothing escapes from inside the event horizon, but the region just beyond this radius can be a seething cauldron of activity. As dust and gas spirals into the black hole, particles are accelerated to almost the speed of light, and this causes them to blast out radiation. How brightly this accretion disk shines depends directly on how much falls into the black hole, says Professor Heino Falcke, a lecturer of Astroparticle Physics and Radio Astronomy at Radboud University Nijmegen in the Netherlands.

"With the equivalent of one Sun per year, [falling into a supermassive black hole], it would emit 1,000, billion, billion, billion gigawatts, which is roughly 200 times the output of the entire Milky Way. But the black hole at the centre of the Milky Way emits much less - around a hundred times the output of the Sun, mostly as radio and X-rays."

That's because very little matter is currently falling into it, says Professor Falcke. "The fact that Sagittarius A* is much fainter than this shows that a black hole is not always the master chef of the galactic crock pot. It can only cook up what happens to be in its local vicinity. This is a black hole on a starvation diet!"

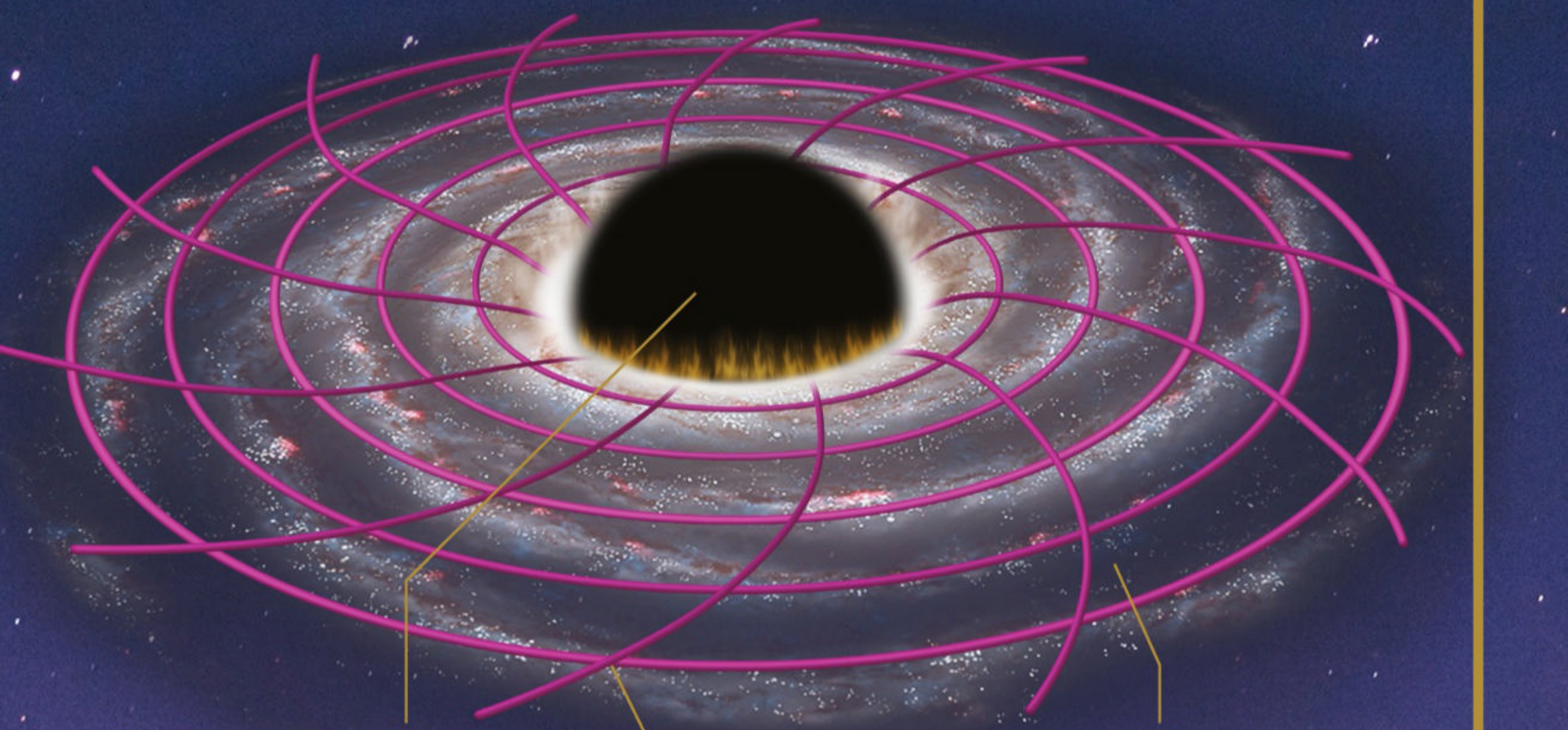
As well as being faint, Sagittarius A* is about 26,000 light years away. At that distance, even the 305-metre Arecibo radio telescope in Puerto Rico will just see a black hole as a single point source of energy. To even contemplate taking a picture that's detailed enough to show the event horizon, you need to use something called Very Long Baseline Interferometry (VLBI).

"Very Long Baseline Interferometry works by combining the data from multiple telescopes," explains Professor Falcke. "The incoming photons are digitised and stored on a hard disk as virtual

> "To grow to their current size, they had to have been suitably placed in regions with a lot of gas to accrete" **Professor Fulvio Melia**

## Target: Milky Way

The supermassive giant at the centre of our galaxy, Sagittarius A* is the prime focus

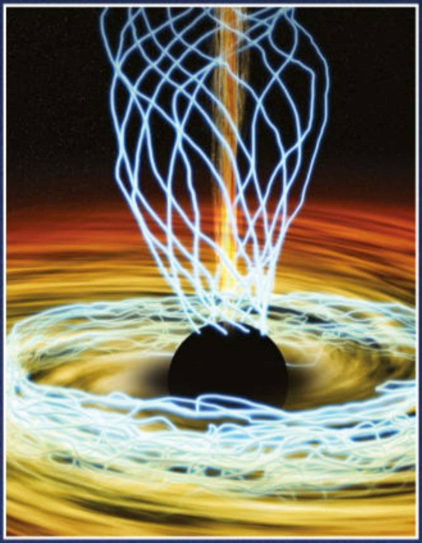


**Sagittarius A***
It's difficult for astronomers to observe the centre of our galaxy due to the dust between it and us. In order to peer into its black hole – Sagittarius A* – we need to use radio wavelengths – the spectrum that the Event Horizon Telescope operates in.

**Space-time**
The fabric of the universe is comprised of three-dimensional space fused with time.

**Magnetic field**
Further evidence for possibly entangled magnetic field lines was reported in early 2015, when an X-ray flare some 400 times brighter than usual erupted from Sagittarius A*.

The core of the Milky Way, seen from the Chandra X-ray Observatory



Supermassive black holes are often found at the centre of galaxies and possess strong magnetic fields

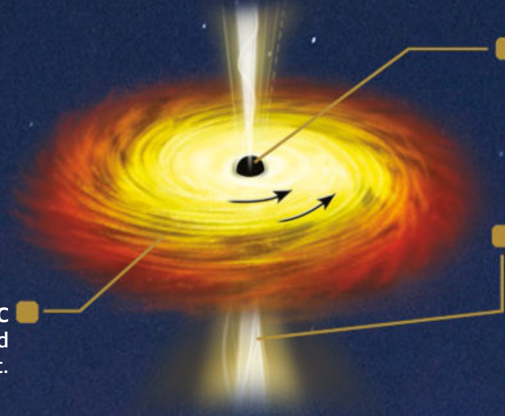
The CARMA telescope array provided vital early data for the Event Horizon Telescope

# How the Event Horizon Telescope will work

The planet-sized array will use cutting-edge technology to reveal the edge of a black hole

## Cloaking Device

Everything inside the event horizon of a black hole is forever hidden from view, because not even light can escape. But just outside this, the matter spiralling inwards shines brightly.



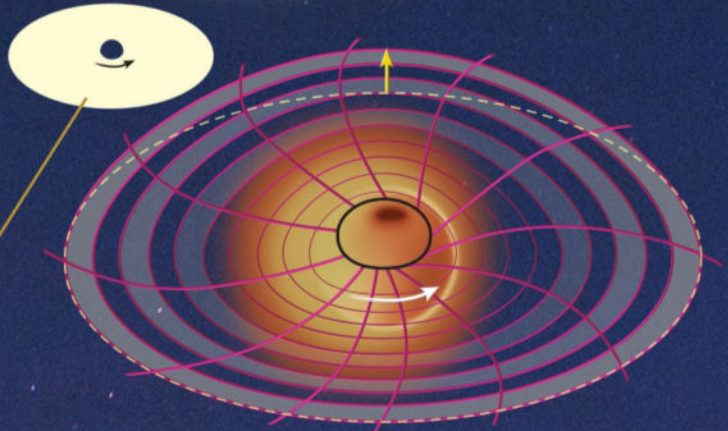
**Event horizon**
Beyond this radius, the escape velocity exceeds the speed of light.

**Polar jets**
Spinning black holes spew jets of ionised matter at relativistic speeds, from each pole.

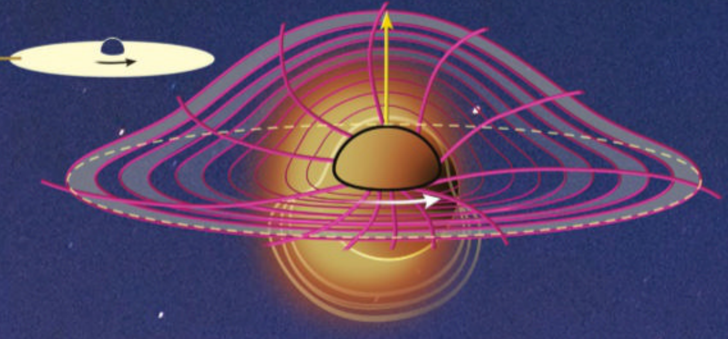
**Accretion disc**
Dust and gas gets accelerated almost to the speed of light.

## Gravitational lens

Light that passes close to the event horizon gets deflected, as if it was passing through a lens. This warps the circular accretion disk from our point of view.



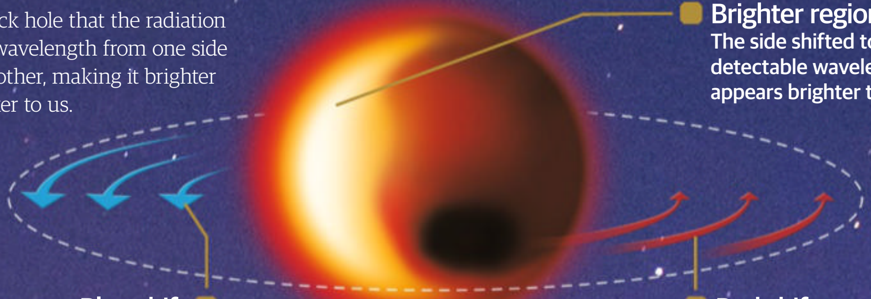
**Face on**
If the accretion disk is nearly perpendicular to us, the gravitational lens effect is small.



**Edge on**
At oblique angles, the image is bent upwards, showing us behind the black hole.

## Glowing banana

Matter orbits so fast close to the black hole that the radiation shifts wavelength from one side to the other, making it brighter or darker to us.



**Brighter region**
The side shifted towards detectable wavelengths appears brighter to us.

**Blue shift**
Light moving towards Earth gets squashed towards shorter wavelengths.

**Red shift**
Light moving away from Earth is stretched into longer wavelengths.

# Makeup of a black hole telescope

These observatories have joined up, like Voltron, to form a single super-telescope

### Arizona Radio Observatory Submillimetre Telescope

**Location:** Mt. Graham, Arizona, USA
**Size of telescope:** 10m
**Owned by:** Steward Observatory, University of Arizona

The summer weather is too moist for short wavelengths to penetrate the atmosphere.

### Large Millimetre Telescope

**Location:** Sierra Negra, Mexico
**Size of telescope:** 50m
**Owned by:** National Institute of Astrophysics, Optics and Electronics, University of Massachusetts

Mexico's largest scientific project, it is integral in improving the EHT's array.

### Combined Array for Research in millimetre-wave Astronomy (CARMA)

**Location:** Cedar Flat, California, USA
**Size of array:** 23 telescopes, 10.4m-3.5m
**Owned by:** Caltech

The CARMA array was used for some of the initial measurements to determine the size of the event horizon at Sagittarius A*.

### Submillimetre Array (SMA)

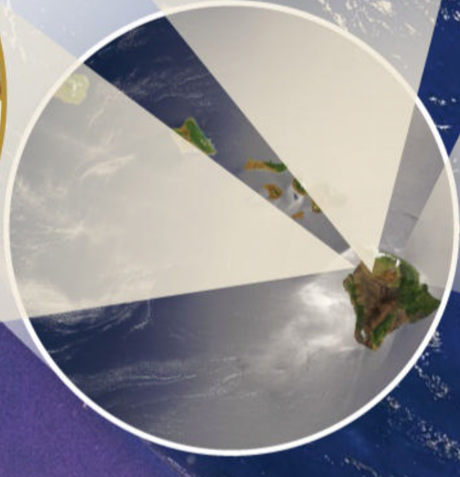
**Location:** Mauna Kea, Hawaii, USA
**Size of array:** 8 telescopes, 6m each
**Owned by:** Smithsonian Astrophysical Observatory, and Academic Sinica Institute

The SMA uses interferometry to combine the signals gathered by each dish to give an effective aperture of 509m for the whole array.

### James Clerk Maxwell Telescope (JCMT)

**Location:** Mauna Kea, Hawaii, USA
**Size of telescope:** 15m
**Owned by:** East Asian Observatory

Operating since 1987, the JCMT is the one of the largest single dish radio telescopes designed to specifically operate at wavelengths shorter than 1mm.



### Caltech Submillimetre Observatory (CSO)

**Location:** Mauna Kea, Hawaii, USA
**Size of telescope:** 10.4m
**Owned by:** Caltech

The data gathered here was used to refine early measurements by the EHT project, and also to push ahead the construction of much larger radio telescope arrays.

copies. We can then replay the data from each telescope and make them behave as if they had come through a single, much larger telescope. There are gaps in between, but this doesn't mean we have gaps in the image; it means we have a blurrier image, like a compressed JPEG."

The Event Horizon Telescope is actually a collection of telescopes positioned around the world. In 2007, the project had just three sites in Hawaii, Arizona and California but it was still able detect a structure around Sagittarius A* that matched predicted sizes for the event horizon. Every year since then they have added more observatories to improve the resolution of the image they receive. "Since 2007 we have made the first detection of ordered magnetic fields around Sagittarius A* [as well as] asymmetric structure around the black hole," says Dr Sheperd Doeleman, Director of the EHT project.

But even the EHT wouldn't be able to see Sagittarius A* were it not for the gravitational lensing effect of the black hole's enormous gravity. This distorts the light shining from behind the black hole to create a shadow of the event horizon that appears around five times wider from our perspective. The EHT has measured the visual diameter of this shadow at 37 micro-arcseconds, but until now there haven't been enough telescopes in the array to supply the amount of data to actually produce an image of it. Then, in April 2017, the EHT ran observations over five nights with seven telescopes that combined to give an image resolution of 20 micro-arcseconds. This is just barely enough, according to Professor Melia. "Trying to image the shadow is like trying to image a grapefruit on the Lunar surface. In order for us even get to the point where we have eight pixels across the shadow, we need to use the whole Earth as an aperture."

3 million gigabytes of data for an image eight pixels across might seem excessive, but that's because of the incredible precision with which the telescopes record the faint signal. "The radio waves are very high frequency, which means that there is more data to record during a given time span, and so even after compressing the data, there is still a huge amount to record. It's analogous to writing down the notes of a song versus recording the entire song," explains Eric Agol, Professor of Astronomy at the University of Washington. "A typical telescope just records the photons (like musical notes), while VLBI needs to record the radio waves (like sound waves of music)."

According to Professor Falcke, this digitising technique quickly inflates the amount of data. "The EHT uses 2-bit sampling, so each photon is converted to a 0, 1, 2 or 3, depending on the amplitude of the signal. Each telescope takes eight billion samples per second in two different polarisations at once. Over the course of one night, a telescope might generate six to eight hours of data and there are seven telescopes at six locations in the EHT."

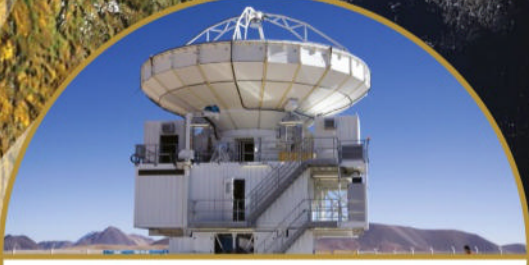
As well as Sagittarius A*, there is one other supermassive black hole that is in range of the EHT. It lies at the centre of the M87 elliptical

**Event horizon telescope size:**
12,600km

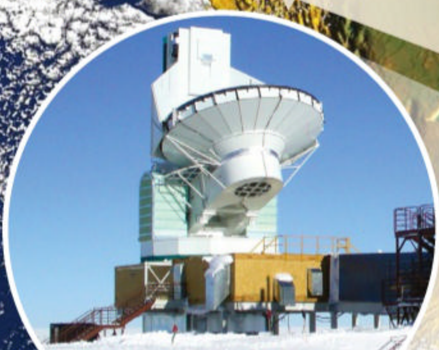
**Event horizon telescope resolution:**
<25 micro-arcseconds

**IRAM**
**Location:** Sierra Nevada, Spain
**Size of telescope:** 30m
**Owned by:** Institut de Radioastronomie Millimétrique
The observatory operates 24 hours a day on every day of the year and still only has time for one third of the projects.

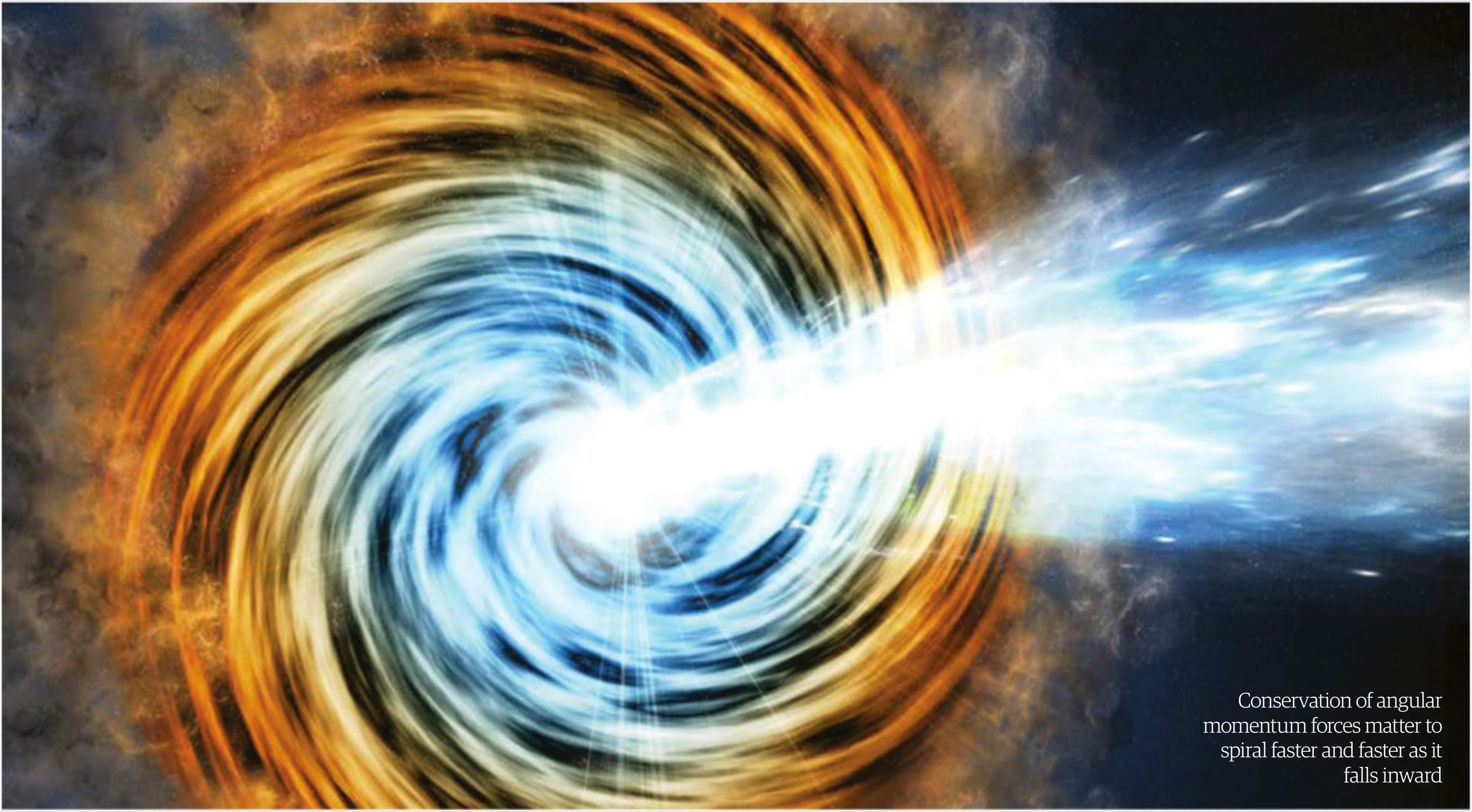
**Atacama Submillimetre Telescope Experiment (ASTE)**
**Location:** Pampa La Bola, Northern Chile
**Size of telescope:** 10m
**Owned by:** National Astronomical Observatory of Japan
Jointly run by several Japanese and Chilean universities, it's operated in Japan.



**Atacama Pathfinder Experiment (APEX)**
**Location:** Llano de Chajnantor, Northern Chile
**Size of telescope:** 12m
**Owned by:** European consortium
The Atacama desert is one of the driest places on Earth, which is ideal for sub-millimetre radio astronomy. At 5,100m, this telescope also sits at the highest altitude in the array.



The 10m South Pole Telescope will soon expand the coverage of the EHT array



Conservation of angular momentum forces matter to spiral faster and faster as it falls inward

The supercomputer at the Atacama Large Millimetre Array correlates signals from each dish

Galaxy M87 contains a supermassive black hole that's within reach of the Event Horizon Telescope

> "With VLBI… a complex algorithm needs to be applied to the data for a picture to be generated" **Pierre Christian**

galaxy in the constellation Virgo. This is one of the largest galaxies in the universe and its black hole is 1,500 times larger than ours. Unfortunately, it is also 2,000 times further away, so from our perspective it appears slightly smaller than Sagittarius A*.

These are the only two black holes in the known universe that are near enough and big enough to be imaged by the EHT and even then it requires perfectly clear skies across all the participating observatories simultaneously. The EHT project also has to compete for telescope time with hundreds of other research teams. April's observations managed two full nights of data gathering for each of these black holes.

One of the team responsible for wrangling all this data into a usable picture is Pierre Christian from the Harvard Smithsonian Center for Astrophysics. "With VLBI, astronomers do not automatically get a picture from their data," he says. "A complex algorithm needs to be applied to the data for a picture to be generated. Another difficulty is the fact that the wavelength chosen for the experiment is such that atmospheric effects generate a lot of noise in the data. A large amount of effort has been undertaken by the EHT team to address these massive challenges."

This may seem like a lot of work for such a low-resolution picture, but imaging the event horizon may provide visual confirmation of Einstein's theory of general relativity. Dr Geoffrey Bower is Chief Scientist for Hawaii Operations for the Academica Sinica Institute for Astronomy and Astrophysics. "General Relativity predicts that we will see a crescent shaped image with a diameter that is determined by the mass of the black hole. But what we will [actually] see depends a lot on what the gas and energetic particles near the black hole are doing. Are they flowing towards the black hole in a smooth structure? Are they clumpy? Is there material jetting away at close to the speed of light? All of these things could be happening at once or at different times. This is part of why the experiment is so exciting to carry out. We are looking at this environment for the very first time."

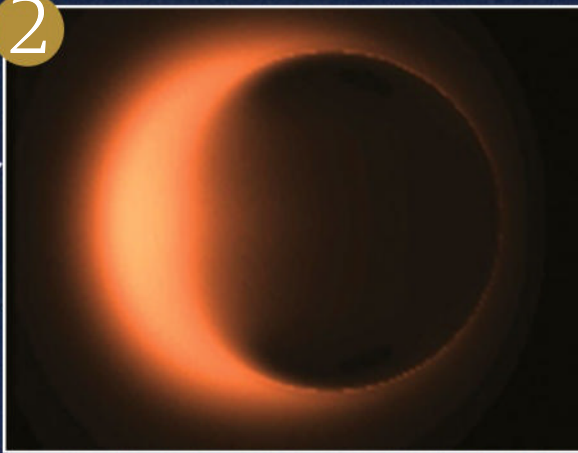
The EHT team took the time necessary to put prepare and release the processed image, and Professor Falcke warned that the first pictures might be slightly disappointing. "A slowly spinning black hole at a modest angle to us should have a shadow that looks like a banana but the final image might look like an ugly peanut. In order to improve on this, the EHT might need to average the data from several years' observations and add a few more telescopes."

In the future, the EHT could also be upgraded with radio telescopes in orbit, but the physics of optics mean these two black holes might still be the only ones we can ever take pictures of. Yet this doesn't diminish the quest's value.

# What we're expecting to see

The Event Horizon Telescope will build an image of Sagittarius A*'s 'point of no return'

2



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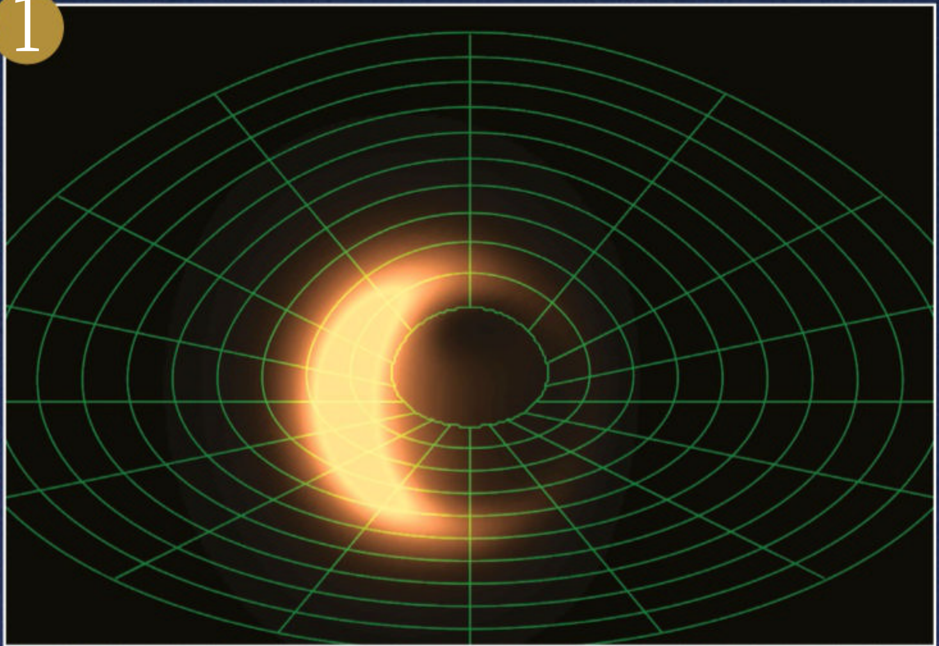

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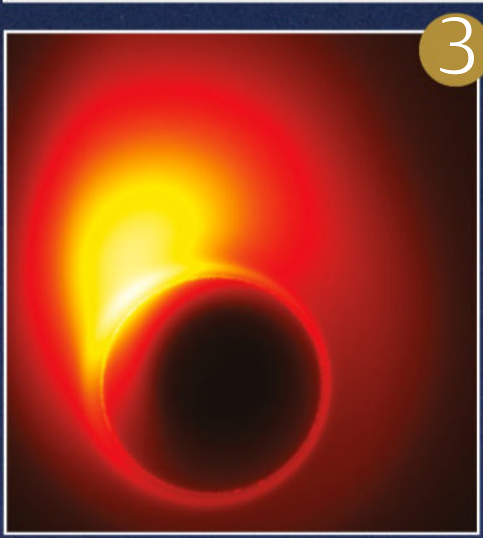


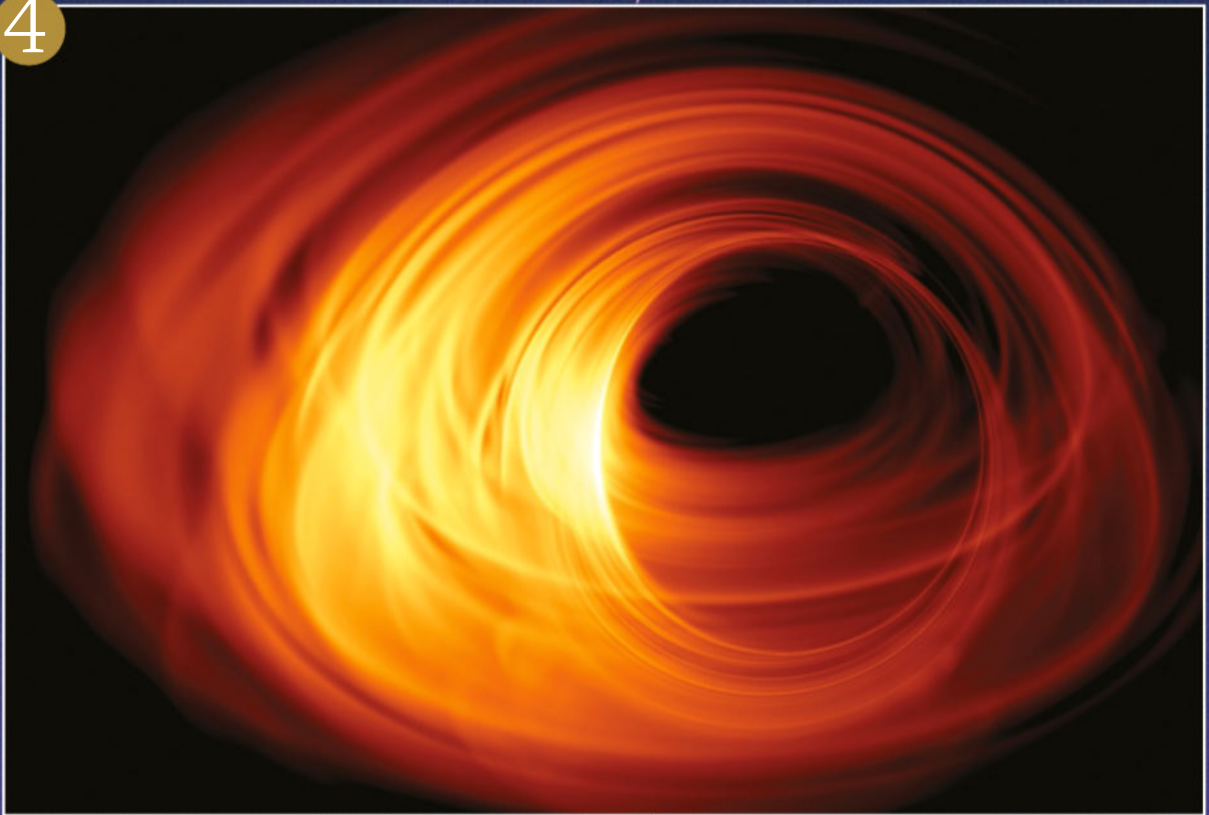
1 A computer simulation shows what a 'hot spot' of gas orbiting a black hole would look like in an extremely high-resolution image.

2 General relativity predicts that Sagittarius A*'s shadow should be circular, however, a black hole could potentially have a prolate or oblate shadow.

3 A simulated event horizon, which shows the appearance of a relativistic jet close to one. Radiation around a black hole is bent by gravity into a ring.

4 The team behind the Earth-sized telescope have produced simulations based on Einstein's theories of what the Milky Way's black hole is most likely to look like.

4



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It's the closest we've come to a picture of a black hole. Made up of images taken on 11 April 2017, this image of Messier 87 shows the event horizon, which is around 2.5 times smaller than the shadow it casts and measuring just under 40 billion kilometres across. We can only expect more great things from the Event Horizon Telescope.

Image source: ESO

# The next generation of gravitational wave detectors

## Some patience will be needed in the hunt for medium-sized black holes

**Written by Paul Sutter**

Medium-sized black holes are some of the most elusive creatures to inhabit the cosmos. Finding them and understanding them will help unravel the mysteries of the growth of supermassive black holes, and the intimate relationship between giant black holes and their host galaxies.

While the medium black holes remain elusive for now, a team of astronomers has devised a strategy for listening to their gravitational wave emissions when they crash into other objects. But we're going to have to wait a while...

A globular cluster - Messier 80 - made up of hundreds of thousands of stars

### The mystery of the middle

Black holes in our universe come in mainly two flavours: relatively small and absolutely gargantuan. The smaller black holes form from the deaths of giant stars, and can have masses anywhere between a handful and a few dozen solar masses (where one "solar mass" is, as you might have guessed, the mass of the Sun). There are billions of these black holes wandering the depths of every galaxy, including the Milky Way, and in the past few decades astronomers have managed to observe quite a fair number.

The gargantuan black holes, however, are truly beasts of a different nature. These things start at a staggering millions of solar masses, and can easily climb their way up to hundreds of billions of times the mass of the Sun. They're much rarer than their diminutive cousins – each galaxy only hosts one (or if they're lucky/unlucky, two), which lurks in its central core.

And that's pretty much it. What we don't see a lot of are the medium-sized black holes, also known as intermediate mass black holes (also, also known as IMBHs). These are hypothetical black holes thought to weigh in at a few thousand times the mass of the Sun. They are the ultimate astrophysical "missing link" – a bridge between the small black holes and the big ones.

And they're very, very hard to find.

### Going big - but not too big

Despite years of searching, astronomers have no conclusive evidence for the existence of any IMBHs. Sure, there are hints and signs here and there – an odd orbit in the center of a cluster, a strange light signal – but nothing definitive.

One of the challenges of finding IMBHs is that we're not exactly sure how and where they form. In one scenario, IMBHs serve as a bridge between small and big black holes. It could be that all black holes start out small (well, smallish – they are still many times more massive than the sun), and over the eons they merge and feed, with a lucky few bulking up to supermassive proportions. According to this model, the IMBHs are simply a stepping stone on the road to greatness, an intermediate step in the normal evolution of giant black holes.

But it could be possible for IMBHs to have their own formation mechanisms, separate from both their smaller and bigger cousins. Perhaps in the early universe giant stars formed (stars far, far larger than any that we see today) and ultimately collapsed, leading directly to black holes of thousands of solar masses.

No matter the case, astronomers think that IMBHs probably hang out in globular clusters. Globular clusters are balls of old, dying stars that orbit a galactic centre, like a decaying town on the outskirts of a major city. While we don't fully understand the origins of globular clusters, it's thought that they might be the remnant cores of dead galaxies, stripped of their star-forming abilities through countless interactions with the larger galaxies.

The Virgo Collaboration

That's why globular clusters may be the ideal place to build IMBHs: either the medium black holes directly formed here but never got the chance to merge with a supermassive black hole, or smaller black holes began merging but were stopped short due to the limited supply of food in the clusters.

### Making waves

This all sounds great, but right now it's hypothetical. Globular clusters are dim and far away, and searching their centres for signs of medium black holes is an incredibly hard task. So astronomers are working hard to come up with ways to detect IMBHs, and

> “IMBHs can occasionally swallow other galactic denizens, up to and including smaller black holes”

An aerial view of the site of the Virgo experiment

recently a team has put together a proposal involving the next generation of gravitational wave detectors.

Just like their supermassive brethren, IMBHs can occasionally swallow other galactic denizens, up to and including smaller black holes. This is relatively rare, however. Orbiting black holes are frustratingly stable – they can just dance in circles around each other for billions of years. In order to make two black holes merge, there has to be a third black hole in the system, destabilising their orbits and triggering the beginning of the merger event.

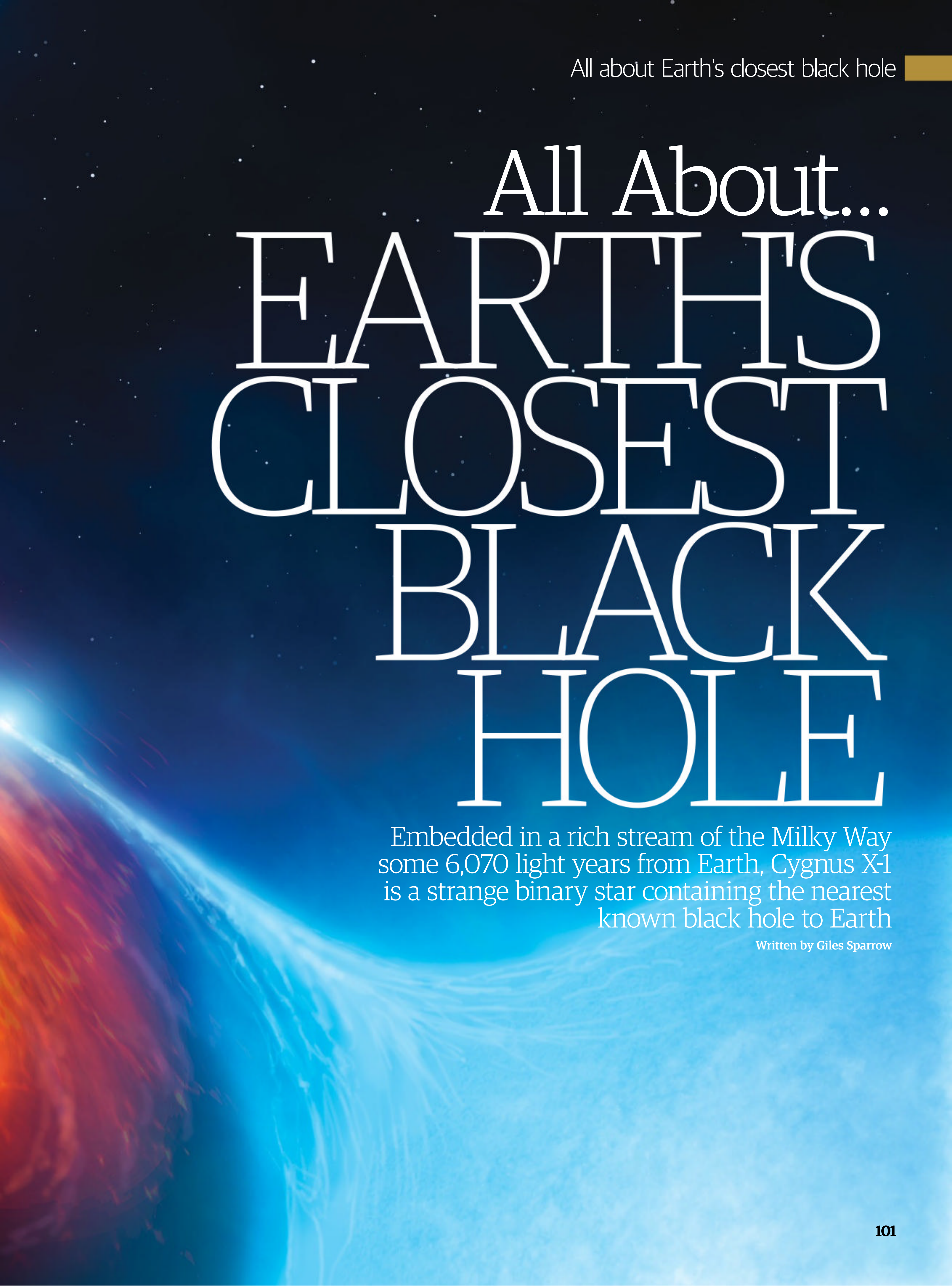
The team of astronomers estimated how often this scenario could happen inside globular clusters, plugging in known and estimated values of star populations, small black hole populations and the theoretical existence of IMBHs. From there, they calculated the emission of gravitational waves from those events, and how frequently those gravitational waves would wash over the Earth.

**THE BAD NEWS:** current gravitational wave detectors, like the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo, don't have the sensitivity to detect these gravitational waves.

**THE GOOD NEWS:** new detectors are right around the corner.

The astronomers estimate that the Laser Interferometer Space Antenna, a planned space-based detector, could spot a few dozen IMBH mergers every year, assuming that the black holes have a mass of a few thousand times that of the sun. It might even be possible for LIGO to detect one or two a year, but only if the IMBHs are around 100 solar masses.

The more we understand IMBHs, the more we learn about the growth and evolution of black holes, their relationships to their host galaxies, and the role they play in the history of the cosmos. We just need better ears.



# All About…

# EARTH'S CLOSEST BLACK HOLE

Embedded in a rich stream of the Milky Way some 6,070 light years from Earth, Cygnus X-1 is a strange binary star containing the nearest known black hole to Earth

**Written by Giles Sparrow**

The distinctive constellation of Cygnus, the Swan, is one of the most famous. It includes the famous Northern Cross asterism and flies south along one of the brightest and nearest parts of the Milky Way, parallel to the Cygnus Rift created by a dust cloud 300 light years from Earth. The brightest star, Deneb, is usually taken to mark the swan's tail, while the beautiful double star, called Albireo, marks its beak. Wings extend to either side of the swan's body, while another bright star, Eta (h) Cygni, lies in the middle of the swan's neck.

Long-exposure photographs reveal a host of faint objects invisible to the naked eye. Not just stars, there are also clouds of interstellar gas such as the North America nebula NGC 7000 (a star-forming region close to Deneb) and the Veil nebula - the remnant of an ancient supernova explosion in the swan's southwestern wing. Invisible radiation wavelengths reveal even more detail - radio telescopes show the full extent of the Cygnus Loop (of which the Veil nebula is a part) and Cygnus A - a pair of huge radio-emitting jets surrounding a distant galaxy. High-energy X-rays uncover the constellation's strangest and best-known object - the black hole Cygnus X-1.

One of the brightest X-ray sources in the entire sky, Cygnus X-1 was discovered in the mid 1960s as a result of an early experiment in space-based astronomy. When Aerobee sounding rockets were launched in 1964 to carry detectors on high-suborbital flights above the atmosphere, they detected eight strong radiation sources from different parts of the sky. Most of them seemed to coincide with distant bright galaxies, but one - less than half a degree away from Eta Cygni in the swan's neck - seemed to have no such association.

In 1970 NASA launched the first dedicated X-ray astronomy satellite, Uhuru, with Cygnus X-1 as a priority for further study. Extended observations showed its X-ray output seemed to be fluctuating several times a second, suggesting it must be coming from a relatively small region, perhaps about the diameter of Saturn.

X-rays are notoriously hard to pin down, however, and the precise location of Cygnus X-1 remained elusive. It was only in 1971, when radio astronomers found that Cygnus X-1 was also a radio source, that astronomers got their first clue to the mystery. At first its radiation seemed to be coming from a distant blue supergiant star, catalogued HD 226868. However, within a few months, astronomers Louise Webster and Paul Murdin of the Royal Greenwich Observatory, as well as Charles Thomas Bolton of the University of Toronto, independently discovered changes in the visible star's spectrum, indicating it moves back and forth every few days. This suggests that it forms a binary system, locked in an orbital waltz with an unseen object of considerable mass that was otherwise completely invisible.

Black holes had been theorised as early as the 1780s, but the physics underlying such bizarre objects weren't described until the 1930s. Before then, they remained an intriguing object for cosmologists and theoretical physicists, but looking at their measurements of Cygnus X-1, astronomers realised they might be observing a black hole for the first time. ●

## Cygnus constellation

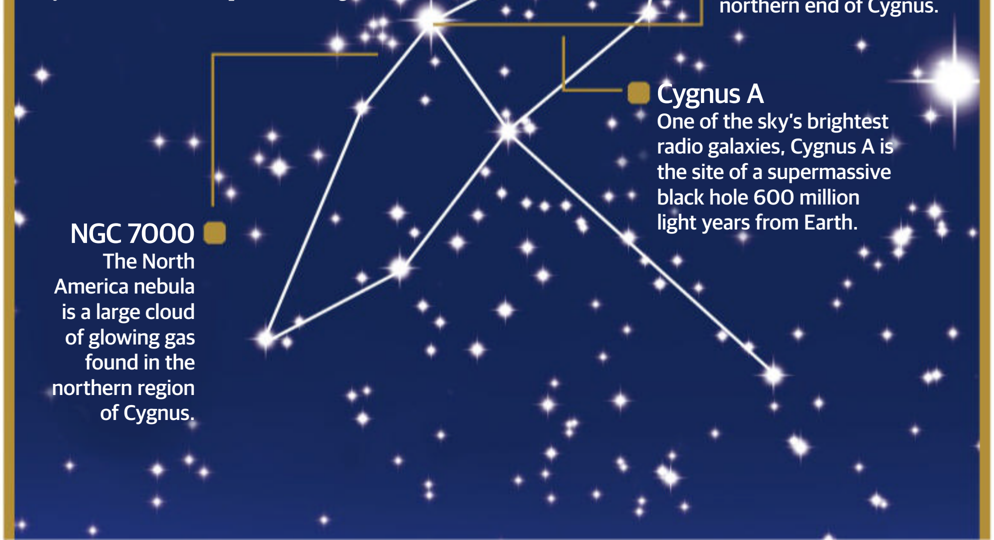
The Tulip nebula, Sharpless 101, is just one of the beautiful but faint objects visible in this night-sky wonder

**NGC 6871**
This small star cluster consists of about 50 newborn blue and white stars.

**X-ray view**
In an image from NASA's Chandra satellite, X-ray emissions from the hot disc around the Cygnus X-1 black hole are dominant, while the companion star HD 226868 disappears.

## Celestial swan

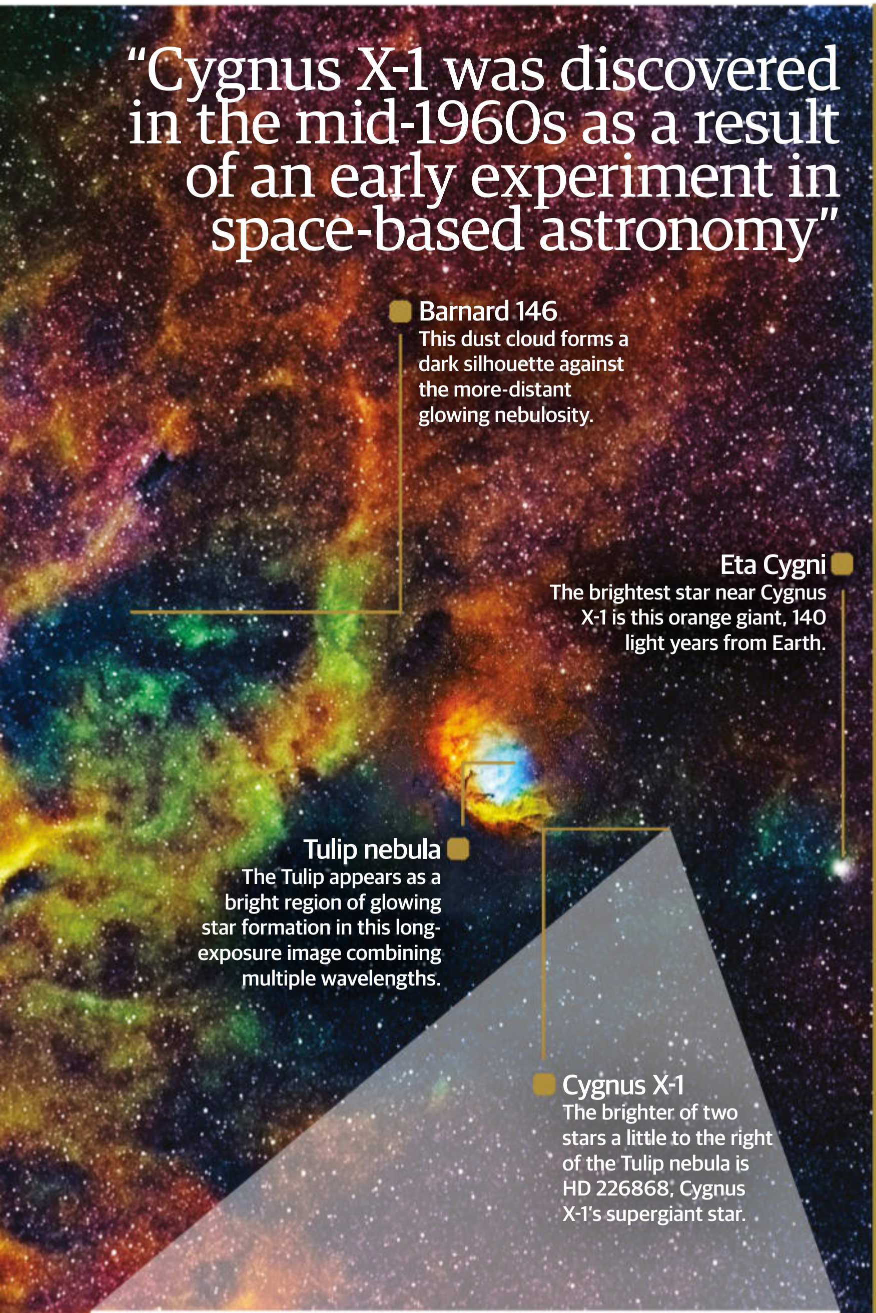
Cygnus forms a large cross with outstretched wings, rising high in Northern Hemisphere skies on summer nights. Deneb of Alpha Cygni marks one corner of the famous Summer Triangle of bright stars, along with Vega in neighbouring Lyra and Altair in Aquila, the Eagle.



**Deneb**
This marks the tail of the swan and lies at the northern end of Cygnus.

**Cygnus A**
One of the sky's brightest radio galaxies, Cygnus A is the site of a supermassive black hole 600 million light years from Earth.

**NGC 7000**
The North America nebula is a large cloud of glowing gas found in the northern region of Cygnus.



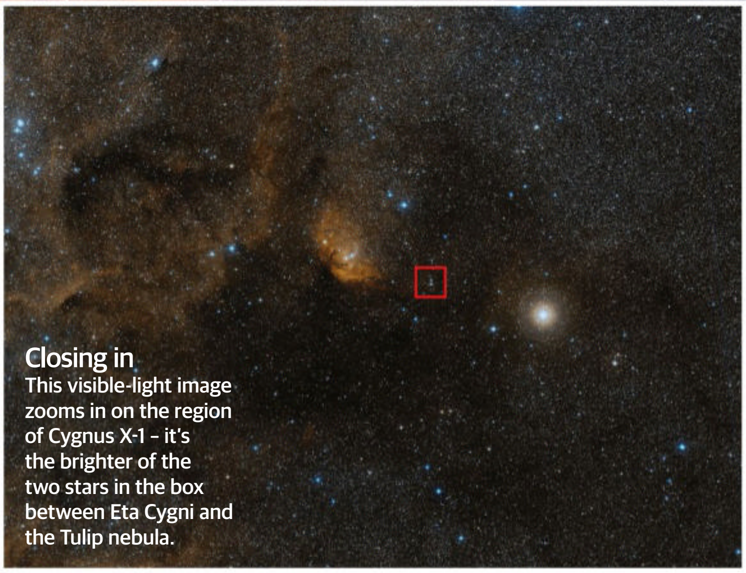
> "Cygnus X-1 was discovered in the mid-1960s as a result of an early experiment in space-based astronomy"

**Barnard 146**
This dust cloud forms a dark silhouette against the more-distant glowing nebulosity.

**Eta Cygni**
The brightest star near Cygnus X-1 is this orange giant, 140 light years from Earth.

**Tulip nebula**
The Tulip appears as a bright region of glowing star formation in this long-exposure image combining multiple wavelengths.

**Cygnus X-1**
The brighter of two stars a little to the right of the Tulip nebula is HD 226868, Cygnus X-1's supergiant star.



**Closing in**
This visible-light image zooms in on the region of Cygnus X-1 – it's the brighter of the two stars in the box between Eta Cygni and the Tulip nebula.

# Cygnus X-1 by numbers

The nearest black hole to Earth is an extreme object in many ways

## 6,070 ly

*Cygnus X-1's distance from Earth according to the most accurate radio measurements.*

## 5.6 days

The period in which the two components of Cygnus X-1 orbit each other.

## 14.8 Suns

*The mass of the Cygnus X-1 black hole, according to the latest research.*

## 0.2 AU

Approximate distance between the black hole and its companion star - 20 per cent of the Earth-Sun distance.

## 800 times per second

The black hole's rotation period.

## 26 km

*The black hole's Schwarzschild radius - the size of its event horizon or point of no return.*

## 350,000 Suns

*Approximate luminosity of the black hole's companion star.*

## 30,000 km

Estimated diameter of the super-hot accretion disc around the Cygnus X-1 black hole.

# Inside Cygnus X-1

## How this binary system has been tearing itself apart in one of the most volatile stellar partnerships

Cygnus X-1's black hole is thought to be the remnant of a massive star that died in a supernova a few million years ago. This brilliant stellar explosion left behind a core so dense and massive that it collapsed beyond the point where any internal pressure could hold it up.

A tiny, impossibly dense point in space known as a singularity was formed, the gravity of which is so great that not even light can escape it. The singularity seals itself off from the external universe within a barrier called an event horizon, marking the last point from which light can overcome its gravity. It's the event horizon that forms the boundary of a black hole as we see it from the external universe – the more massive the singularity, the more powerful its gravity and the larger its event horizon.

So how does this object, that's barely visible, produce the powerful X-rays that make Cygnus X-1 stand out so much? The answer lies in its relationship with its companion star, HD 226868. This stellar monster, with a mass measured to be between 20 and 40 times that of the Sun, pumps out up to 400,000 times as much energy.

As the radiation forces its way out from the star's core, it causes the outer layers to swell up to 17 times the solar diameter, heating the surface to a searing blue-hot 31,000 degrees Celsius (56,000 degrees Fahrenheit).

> "As the radiation forces its way out from the star's core, it causes the outer layers to swell up to 17 times the solar diameter, heating the surface to a searing blue-hot 31,000 degrees"

HD 226868 is classed as a blue supergiant, but like all stars of its kind, it's losing mass rapidly – the high temperatures at its surface cause its outer layers to boil away into space, creating a powerful stellar wind. HD 226868 is thought to shed an entire Sun's worth of material every 400,000 years.

Based on the speed at which the two objects circle one another, astronomers estimate the black hole has a mass of about 14.8 Suns and orbits at only twice the visible star's radius. This is far enough away for the orbit to remain stable, but close enough for the black hole's gravity to distort its companion's shape into something like that of a teardrop. As the star spins on its axis with respect to Earth, we see different amounts of its surface and so its brightness appears to vary slightly.

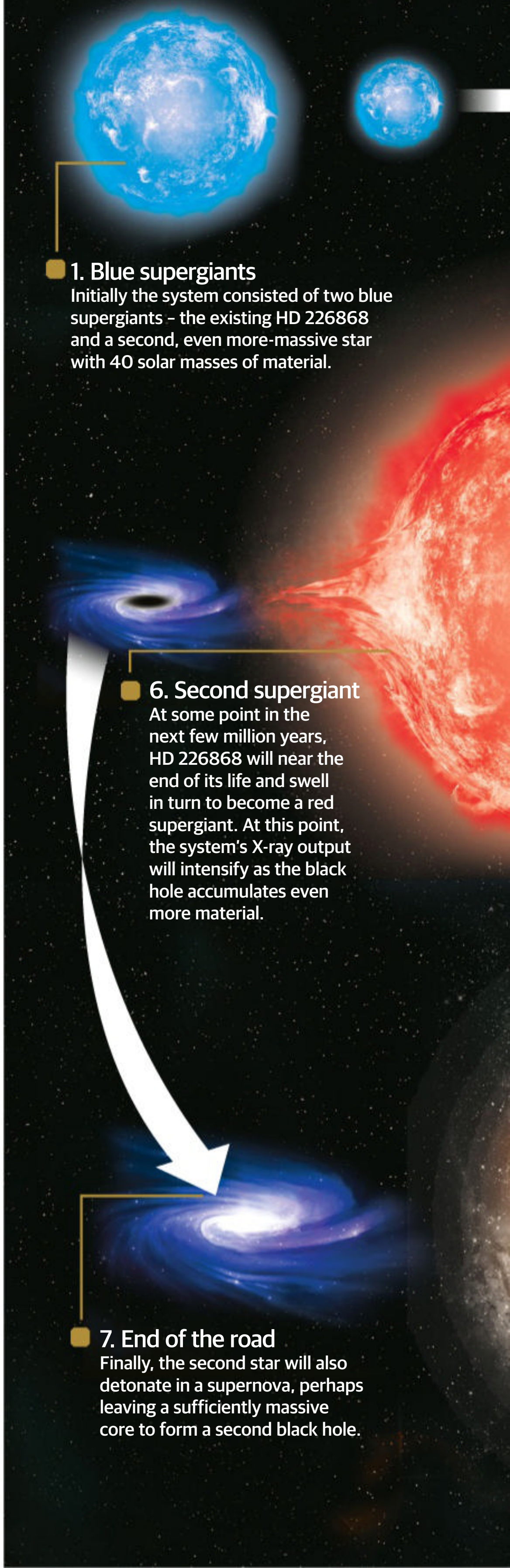
The black hole's gravity isn't quite strong enough to pull material completely away from the star's outer layers (as happens in some other binary systems), but particles ejected into HD 226868's stellar wind are rapidly pulled towards the black hole on a spiral path. The falling material creates a flattened disc around the black hole and friction between gases moving at different speeds in various parts of the disc heats them to very high temperatures.

The innermost regions break down into an electrically charged gaseous plasma at more than 10 million degrees Celsius (18 million degrees Fahrenheit), emitting relatively long-wavelength, soft X-rays. These rays then gain additional energy through a process called Compton scattering, which involves individual photons of radiation interacting with electron particles moving at high speeds within a transparent corona above and below the thick disc. Ultimately this boosts the emitted photons to the hard X-ray part of the spectrum, giving Cygnus X-1 an effective temperature of more than a billion degrees.

Cygnus X-1's X-ray output flickers on a timescale of milliseconds as the amount of gas being fed into the central black hole varies. The output also goes through periodic dips with cycles of 5.6 days and 300 days. These dips seem to be caused by the X-ray disc's partial disappearance behind an intervening doughnut of gas around the supergiant, but the system also displays other patterns that aren't understood. In particular the corona that produces its hard X-rays sometimes disappears, leaving only the more-variable soft X-ray emission behind for scientists to eventually uncover. ●

## Evolving system

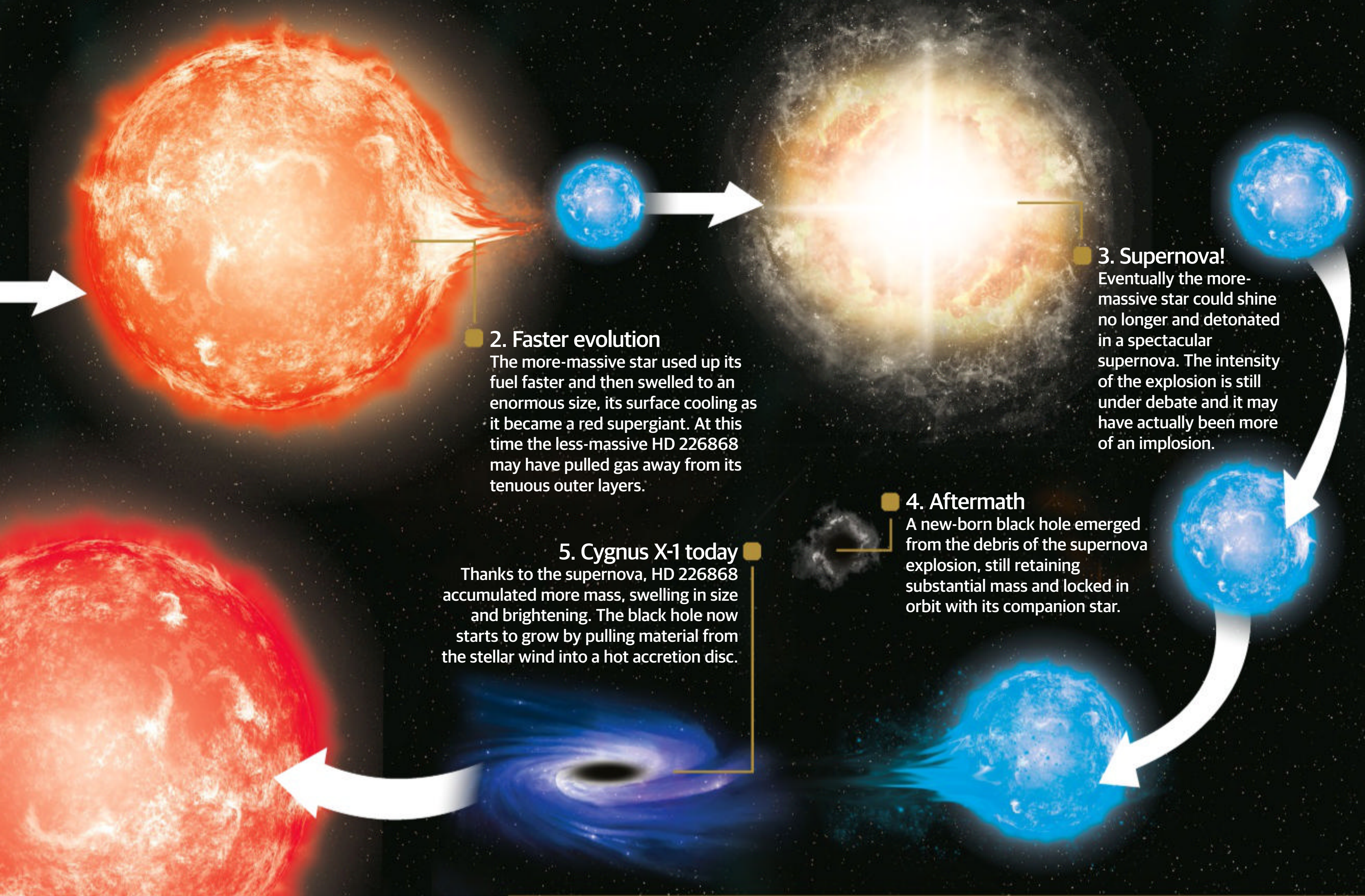
This sequence shows key stages in the past and future development of the unique Cygnus X-1 system



**1. Blue supergiants**
Initially the system consisted of two blue supergiants – the existing HD 226868 and a second, even more-massive star with 40 solar masses of material.

**6. Second supergiant**
At some point in the next few million years, HD 226868 will near the end of its life and swell in turn to become a red supergiant. At this point, the system's X-ray output will intensify as the black hole accumulates even more material.

**7. End of the road**
Finally, the second star will also detonate in a supernova, perhaps leaving a sufficiently massive core to form a second black hole.



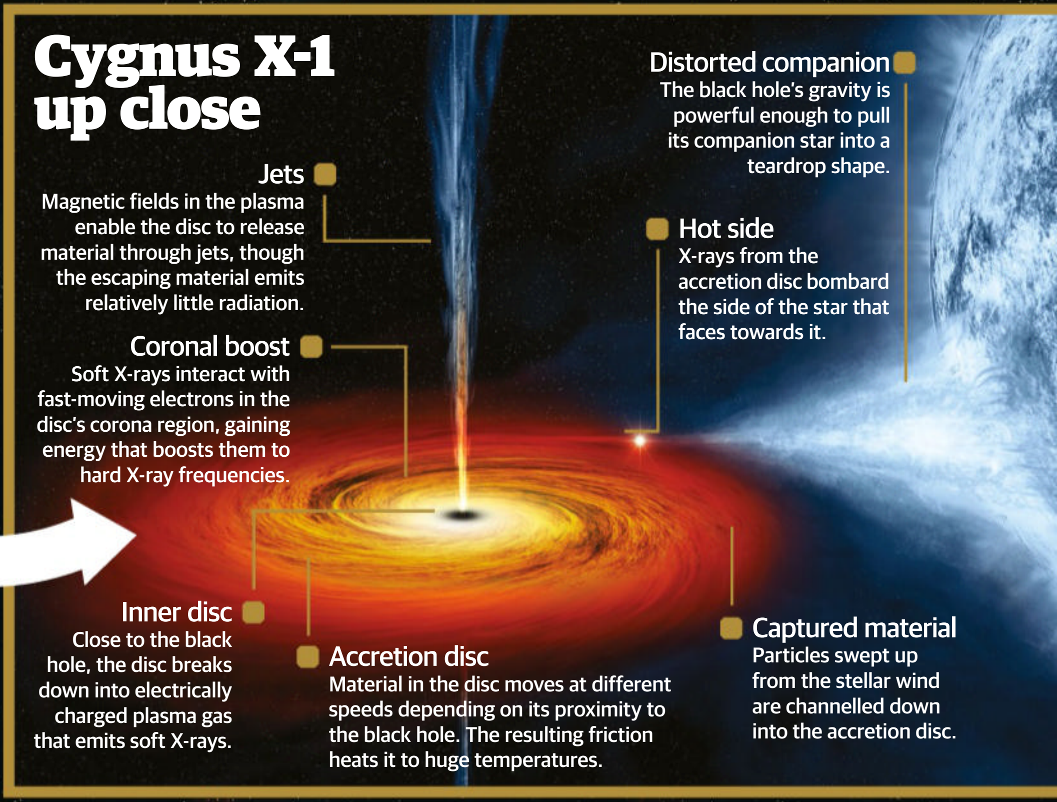
**2. Faster evolution**
The more-massive star used up its fuel faster and then swelled to an enormous size, its surface cooling as it became a red supergiant. At this time the less-massive HD 226868 may have pulled gas away from its tenuous outer layers.

**3. Supernova!**
Eventually the more-massive star could shine no longer and detonated in a spectacular supernova. The intensity of the explosion is still under debate and it may have actually been more of an implosion.

**4. Aftermath**
A new-born black hole emerged from the debris of the supernova explosion, still retaining substantial mass and locked in orbit with its companion star.

**5. Cygnus X-1 today**
Thanks to the supernova, HD 226868 accumulated more mass, swelling in size and brightening. The black hole now starts to grow by pulling material from the stellar wind into a hot accretion disc.

## Cygnus X-1 up close



**Jets**
Magnetic fields in the plasma enable the disc to release material through jets, though the escaping material emits relatively little radiation.

**Coronal boost**
Soft X-rays interact with fast-moving electrons in the disc's corona region, gaining energy that boosts them to hard X-ray frequencies.

**Inner disc**
Close to the black hole, the disc breaks down into electrically charged plasma gas that emits soft X-rays.

**Accretion disc**
Material in the disc moves at different speeds depending on its proximity to the black hole. The resulting friction heats it to huge temperatures.

**Distorted companion**
The black hole's gravity is powerful enough to pull its companion star into a teardrop shape.

**Hot side**
X-rays from the accretion disc bombard the side of the star that faces towards it.

**Captured material**
Particles swept up from the stellar wind are channelled down into the accretion disc.

# Observing a black hole

## Studying an object that lets no light escape is as tricky as it sounds, but innovative telescopes have unlocked unseen layers of space

As the nearest known black hole to Earth, Cygnus X-1 has been subjected to intensive study. Most of what we know has come from satellite-based observatories and particularly orbiting X-ray telescopes. The system is usually the brightest source of hard X-rays in the sky, but generating images from these presents unique challenges. For a start they're extremely hard to focus on, as when they hit a reflecting surface head-on, they tend to either be absorbed or pass straight through it.

Early X-ray astronomy satellites had very low directional resolution – in principle they consisted of a shielded X-ray detector with an open window at one end, so attempts to map the X-ray sky involved scanning and recording the directions from which X-rays entered the detector window.

Fortunately more-recent orbiting telescopes have transformed our view of the X-ray sky. Beginning with the German-led ROSAT satellite (launched in 1990), increasing use has been made of an instrument design first outlined in the 1950s by physicist Hans Wolter. These telescopes use conical metal mirrors whose surfaces lie at fairly shallow angles to the incoming radiation, creating a situation in which X-rays ricochet off the surface and are deflected towards a focus point. By using several sets of concentric mirrors nested within one another, it's possible to form an image of a moderately large area of the sky, which can then be recorded using a solid-state detector fairly similar to the CCDs used in visible-light cameras.

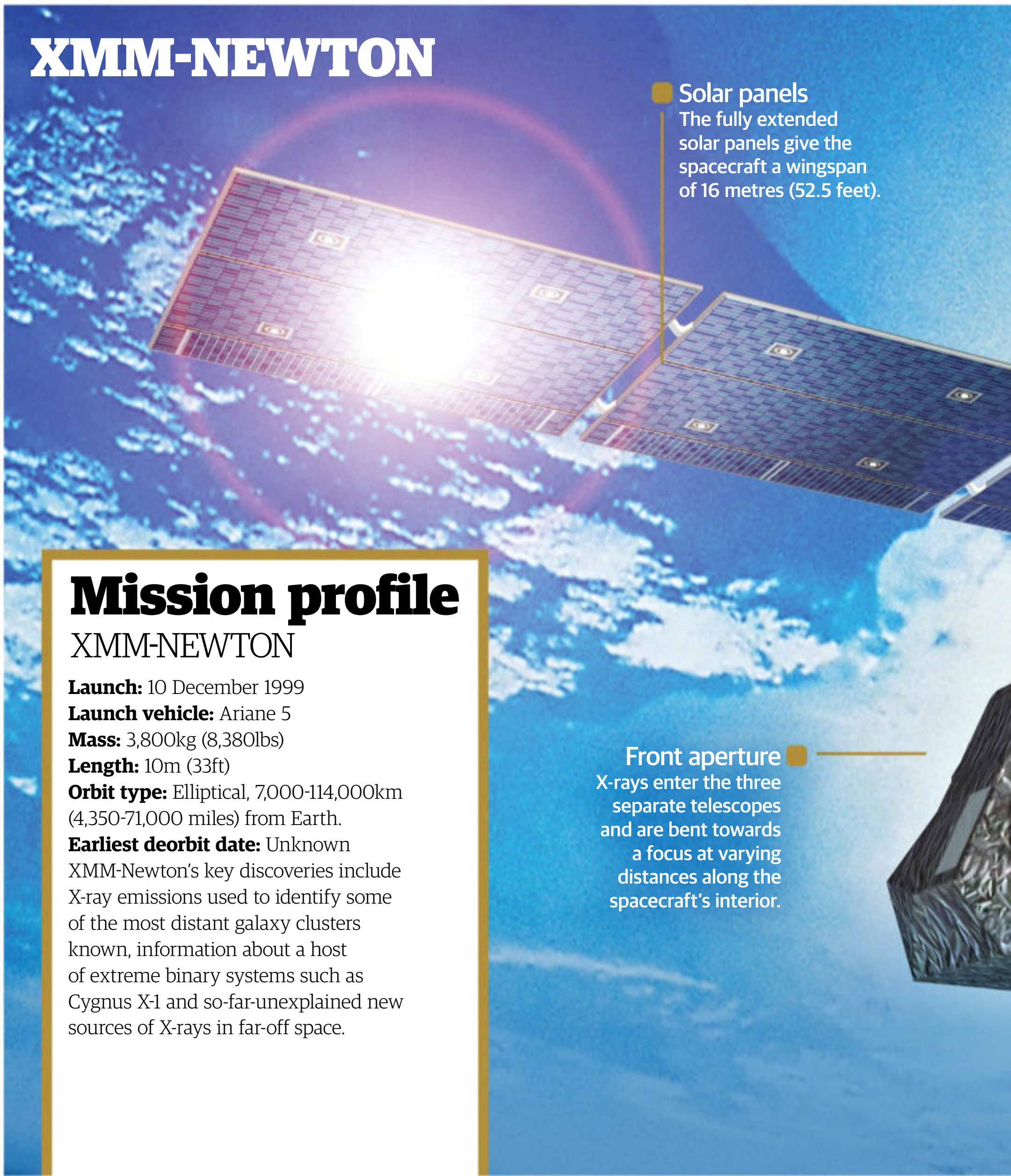
The latest and most-sophisticated X-ray instruments to turn their attention towards Cygnus X-1 are NASA's Chandra X-ray Observatory and the European Space Agency's XMM-Newton (X-ray Multi-Mirror) spacecraft. Both were launched in 1999 and are still operational after a decade and a half in orbit. Chandra has a single telescope assembly using four pairs of nested mirrors to focus X-rays from a small part of the sky at high resolution. XMM-Newton, in contrast, uses no fewer than three separate telescopes with 58 individual mirrors in each to focus X-rays with a variety of different wavelengths, imaging larger areas of the sky than Chandra at lower resolution. Both telescopes also carry spectrometers capable of splitting and analysing X-rays from individual objects according to their energies.

Using observations from Chandra, XMM-Newton and other telescopes, in 2011 astronomers produced the most detailed analysis of the Cygnus X-1 system yet. Radio telescope measurements first pin-pointed the system's position in the sky as seen from opposite sides of Earth's orbit. The slight difference caused by our shifting point of view (an effect called parallax) was used to calculate the system's distance with unprecedented precision, putting it 6,070 light years from Earth. Combined with the optical spectroscopy of the companion star, this enabled researchers to determine that the black hole's mass at 14.8 times the Sun's, and that it moves through its region of space at a fairly sedate speed of about nine kilometres (5.6 miles) per second.

Finally, X-ray studies confirmed the general structure of the system and determined the black hole's rotation rate with unprecedented accuracy, revealing that it spins roughly 800 times a second – close to the maximum theoretical limit.

The sudden loss of mass associated with a traditional supernova explosion has a tendency to give binary systems a kick that throws them across space at high speed and also tends to reduce the speed with which the collapsed stellar core rotates. Cygnus X-1's combination of rapid rotation and slow speed through space suggest it may have formed in another way – a stellar implosion, rather than a true supernova explosion, in which the collapsing black hole simply consumed its progenitor star from within.

If the black hole really did form in this way, it would be the first confirmed example of this kind of highly unusual stellar cataclysm and yet another reason to study the system. Whatever the truth, it seems certain that, five decades on from its discovery and after being the subject of more than 1,000 scientific papers, Cygnus' most famous object isn't ready for its swan song just yet. ●



**Solar panels**
The fully extended solar panels give the spacecraft a wingspan of 16 metres (52.5 feet).

**Front aperture**
X-rays enter the three separate telescopes and are bent towards a focus at varying distances along the spacecraft's interior.

### Mission profile

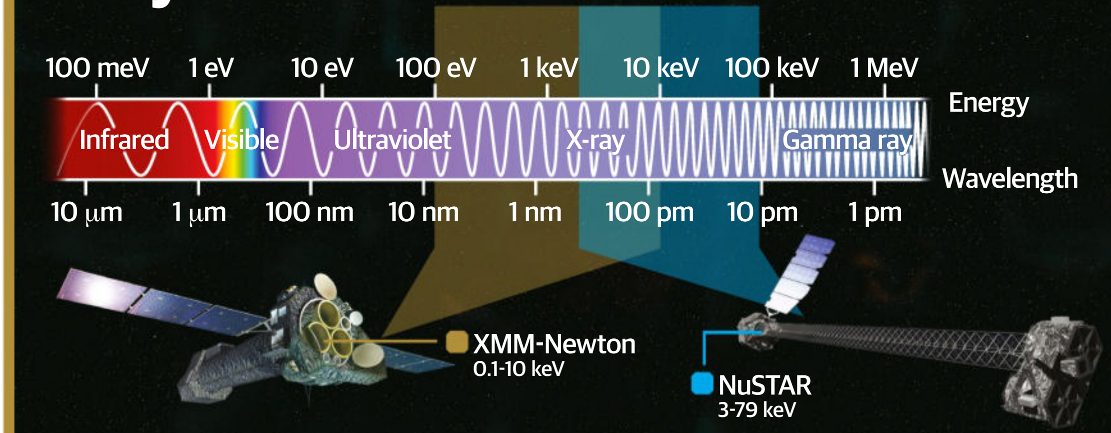
XMM-NEWTON

**Launch:** 10 December 1999
**Launch vehicle:** Ariane 5
**Mass:** 3,800kg (8,380lbs)
**Length:** 10m (33ft)
**Orbit type:** Elliptical, 7,000-114,000km (4,350-71,000 miles) from Earth.
**Earliest deorbit date:** Unknown

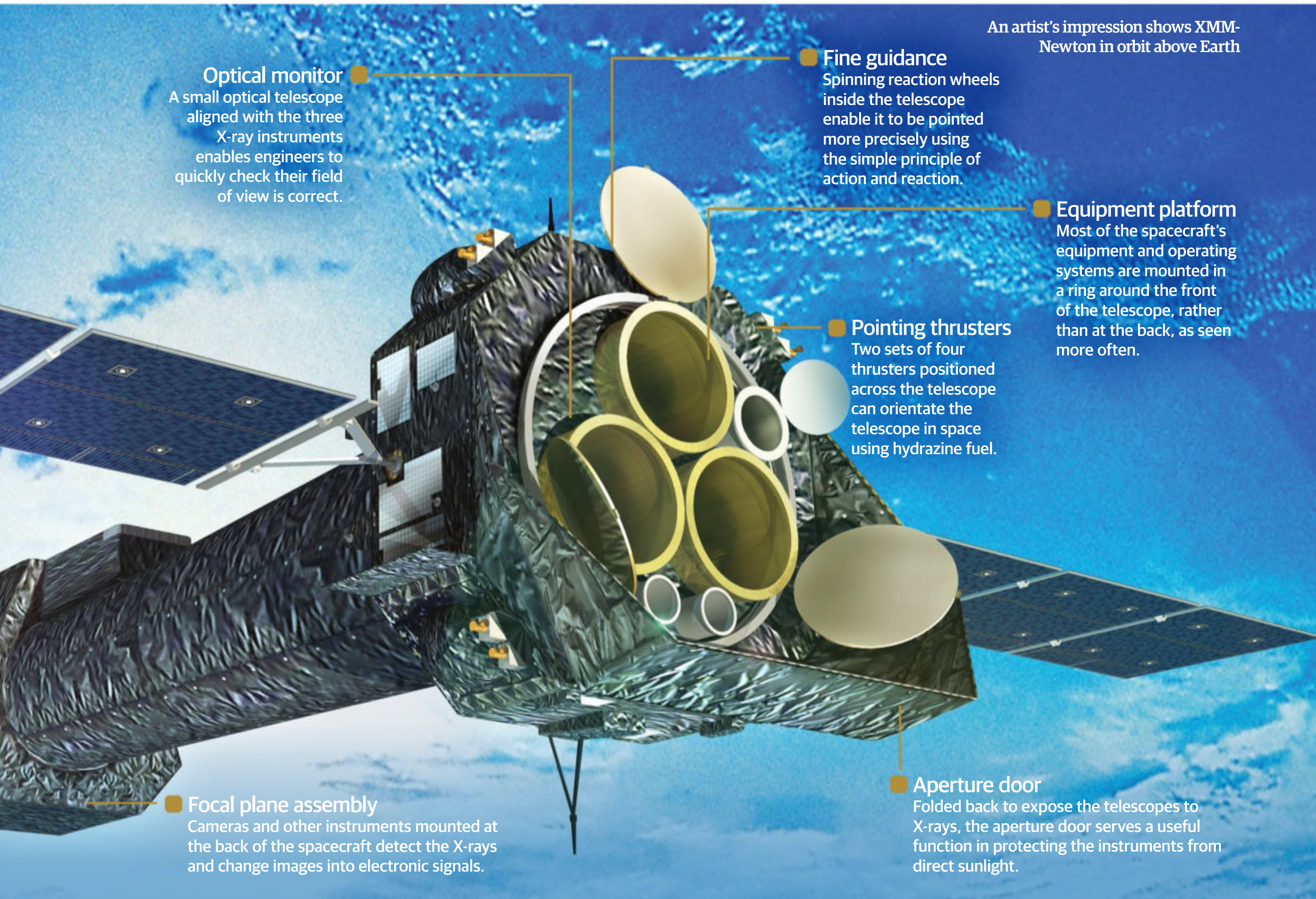
XMM-Newton's key discoveries include X-ray emissions used to identify some of the most distant galaxy clusters known, information about a host of extreme binary systems such as Cygnus X-1 and so-far-unexplained new sources of X-rays in far-off space.

XMM-Newton undergoes testing at the European Space Research and Technology Center in the Netherlands

## X-ray detection



X-ray wavelengths range from around ten nanometres at their longest, down to just ten picometres (1,000 times shorter) at their shortest. The shorter the wavelength of an X-ray photon, the more energy it packs in and X-ray energies range from 100 electronvolts (eV) up to 100 kiloelectronvolts (keV) - the standard units of energy measurement in everyday situations. XMM-Newton images X-rays with energies of up to ten keV, covering all soft X-rays and many hard X-rays. NASA's NuSTAR telescope was built to detect even the higher energies associated with phenomena such as supermassive black holes - monsters that are millions of times more massive than Cygnus X-1.



An artist's impression shows XMM-Newton in orbit above Earth

**Optical monitor**
A small optical telescope aligned with the three X-ray instruments enables engineers to quickly check their field of view is correct.

**Fine guidance**
Spinning reaction wheels inside the telescope enable it to be pointed more precisely using the simple principle of action and reaction.

**Equipment platform**
Most of the spacecraft's equipment and operating systems are mounted in a ring around the front of the telescope, rather than at the back, as seen more often.

**Pointing thrusters**
Two sets of four thrusters positioned across the telescope can orientate the telescope in space using hydrazine fuel.

**Focal plane assembly**
Cameras and other instruments mounted at the back of the spacecraft detect the X-rays and change images into electronic signals.

**Aperture door**
Folded back to expose the telescopes to X-rays, the aperture door serves a useful function in protecting the instruments from direct sunlight.

# Up close with a monster

## A new project hopes to teach us more about black holes by uniting telescopes around the world

Cygnus X-1 might be the nearest black hole and the first to be discovered, but it's no longer the most famous - that title goes to Sagittarius A*, a supermassive black hole with the mass of over 4 million Suns that lies at the centre of our galaxy.

First hypothesised in the early 1970s, this black hole behemoth's existence was confirmed in 2002 when astronomers measured nearby stars orbiting it at high speed. While stellar-mass black holes typically have event horizons just a few tens of kilometres across, Sagittarius A* is many times the size of the Sun. This means that, even across a distance of 26,000 light years, it offers our best hope for observing a black hole directly.

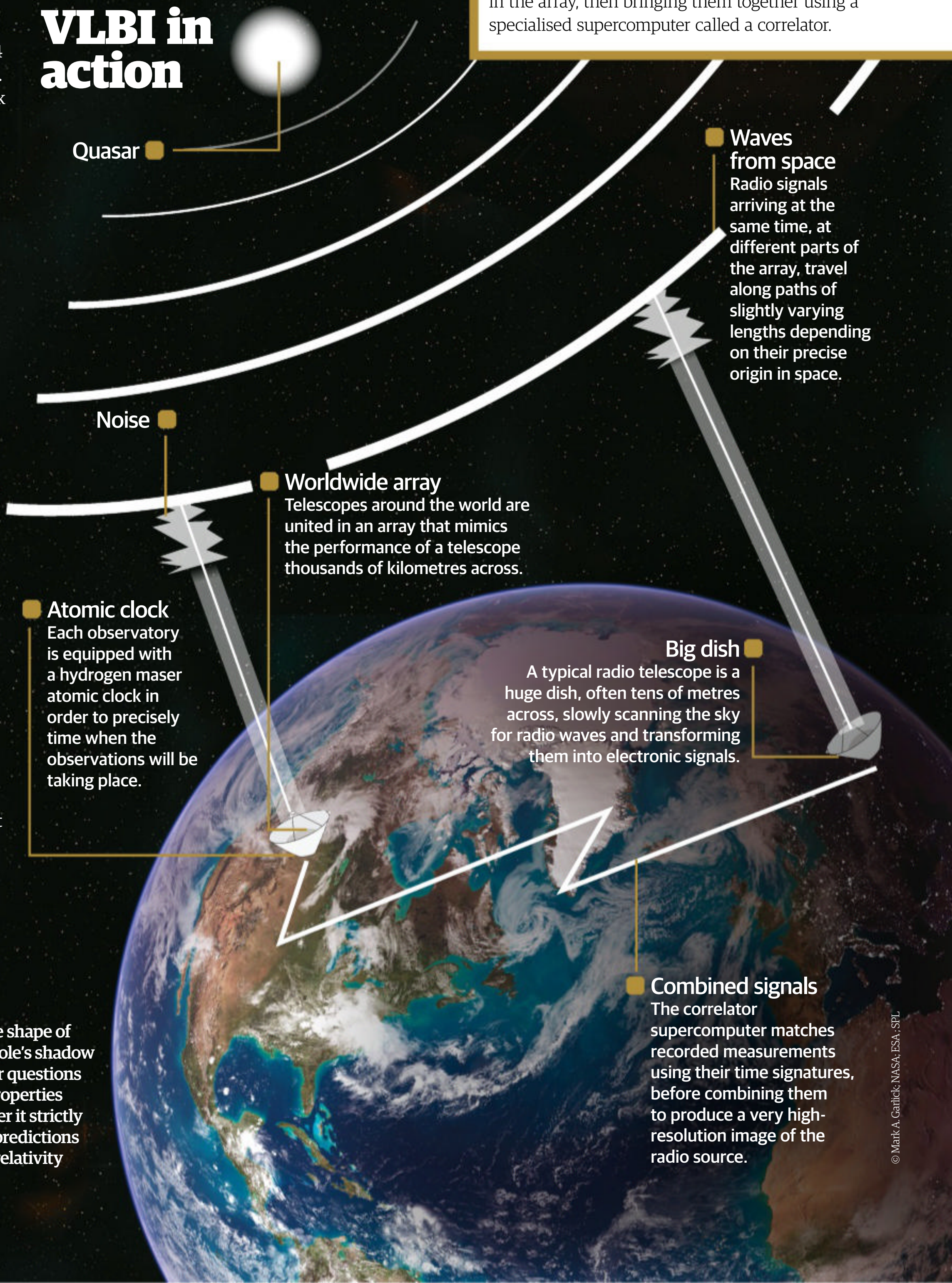
Unfortunately this supermassive singularity long ago swept the region of space around it clear of substantial material, so while it can certainly emit X-rays when occasional debris strays into its path, at the moment it remains frustratingly placid. The only radiation coming from the region takes the form of infrared and radio waves produced as small amounts of gas sift gently into the black hole.

These long-wavelength rays present a huge challenge to astronomers trying to see the intricate details of Sagittarius A*. For a given diameter of telescope, they produce much lower-resolution images than visible light or X-rays, so the only solution is to go big. For an object as small and distant as this, that means a telescope the size of the Earth. The Event Horizon Telescope (EHT) is an international project aimed at linking existing radio telescopes around the world into a huge array with the power to resolve objects down to the apparent diameter of an orange on the surface of the Moon. The team behind it hopes to detect phenomena such as the predicted shadow created as radiation is deflected by the black hole's gravity. If they succeed, they may be able to extend the technique into space, targeting far smaller objects like Cygnus X-1.

### The Event Horizon Telescope

The EHT makes use of a technique known as Very Long Baseline Interferometry (VLBI). This involves making precisely synchronised observations of the same object from widely separated telescopes: radio waves will have had to travel slightly different distances to reach each of the different observatories. By measuring the differences in the length of their paths, it's possible to synthesise an image with the level of detail that would be achieved by an enormous telescope. In practise, this form of VLBI is achieved by recording simultaneous observations at all the telescopes in the array, then bringing them together using a specialised supercomputer called a correlator.

### VLBI in action



**Quasar**

**Noise**

**Waves from space**
Radio signals arriving at the same time, at different parts of the array, travel along paths of slightly varying lengths depending on their precise origin in space.

**Worldwide array**
Telescopes around the world are united in an array that mimics the performance of a telescope thousands of kilometres across.

**Atomic clock**
Each observatory is equipped with a hydrogen maser atomic clock in order to precisely time when the observations will be taking place.

**Big dish**
A typical radio telescope is a huge dish, often tens of metres across, slowly scanning the sky for radio waves and transforming them into electronic signals.

**Combined signals**
The correlator supercomputer matches recorded measurements using their time signatures, before combining them to produce a very high-resolution image of the radio source.

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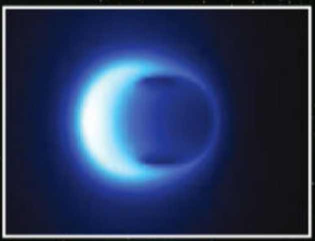


The precise shape of the black hole's shadow will answer questions about its properties and whether it strictly obeys the predictions of general relativity

# A closer black hole?

## 'The Unicorn' lies a mere 1,500 light-years from us and is just three times more massive than the Sun

Written by Mike Wall

Astronomers have apparently found the closest known black hole to Earth, a weirdly tiny object dubbed 'The Unicorn' that lurks just 1,500 light-years from us.

The nickname has a double meaning. Not only does the black hole candidate reside in the constellation Monoceros ('the unicorn'), but its incredibly low mass - about three times that of the Sun - makes it nearly one of a kind.

"Because the system is so unique and so weird, you know, it definitely warranted the nickname of 'The Unicorn'," discovery team leader Tharindu Jayasinghe, an astronomy PhD student at The Ohio State University, said in a new video the school made to explain the find.

But The Unicorn isn't alone. It has a companion - a bloated red giant star that's nearing the end of its life. (Our Sun will swell up as a red giant in about five billion years.) That companion has been observed by a variety of instruments over the years, including the All Sky Automated Survey and NASA's Transiting Exoplanet Survey Satellite.

Jayasinghe and his colleagues analysed that big dataset and noticed something interesting: the red giant's light shifts in intensity periodically, suggesting that another object is tugging on the star and changing its shape.

The team determined that the object doing the tugging is likely a black hole - one harbouring a mere three solar masses, based on details of the star's velocity and the light distortion. (For perspective: the supermassive black hole at the heart of our Milky Way galaxy packs about 4.3 million solar masses.)

"Just as the Moon's gravity distorts the Earth's oceans, causing the seas to bulge toward and away from the Moon, producing high tides, so does the black hole distort the star into a football-like shape with one axis longer than the other," study co-author Todd Thompson, chair of Ohio State's astronomy department, said in a statement. "The simplest explanation is that it's a black hole - and in this case, the simplest explanation is the most likely one."

That explanation, likely though it may be, is not set in stone; The Unicorn remains a black hole candidate at the moment.

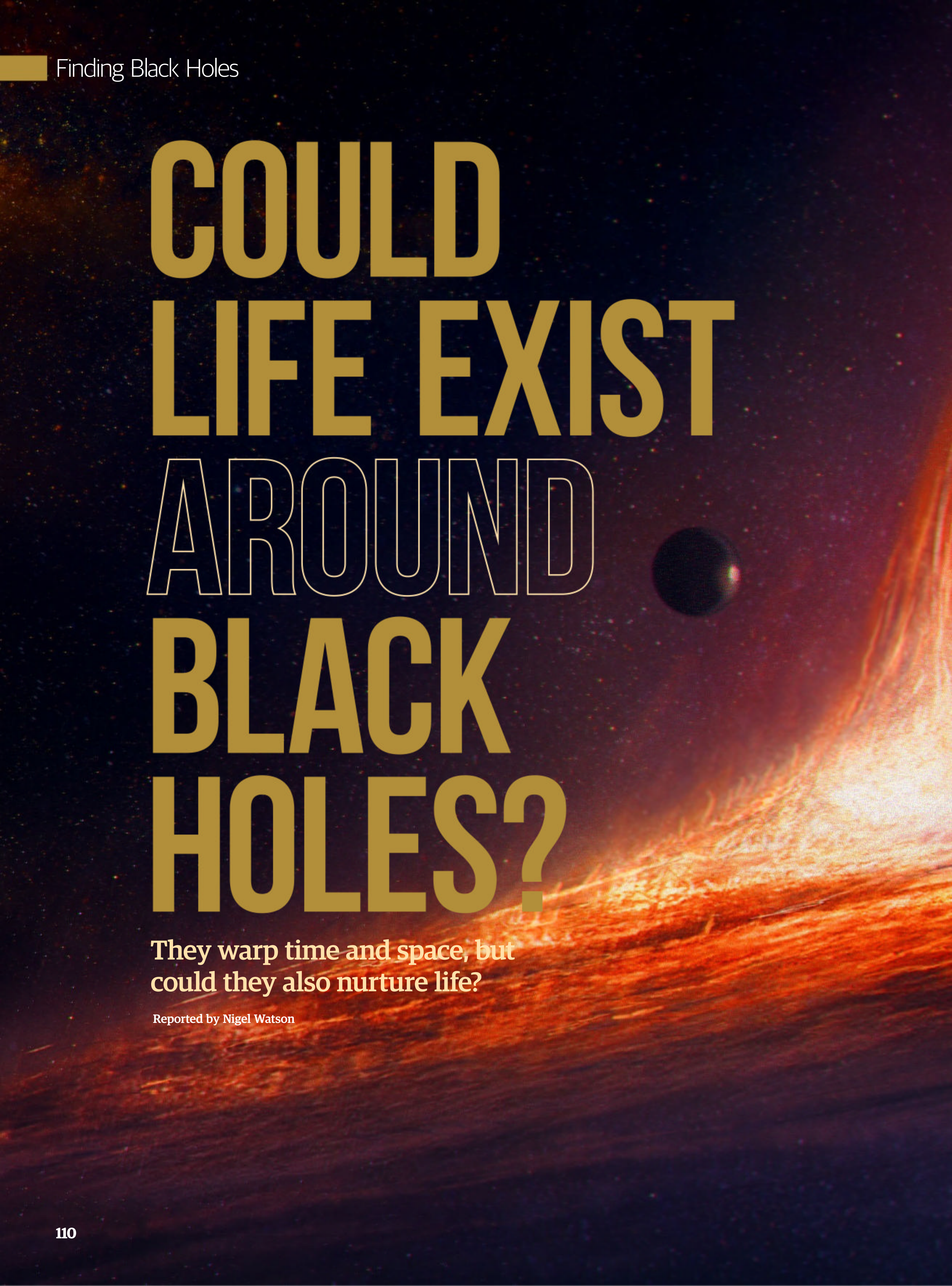
Very few such super-lightweight black holes are known, because they're incredibly hard to find. Black holes famously gobble up everything, including light, so astronomers have traditionally detected them by noticing the impact they have on their surroundings (though we did recently get our first direct image of a black hole, thanks to the Event Horizon Telescope). And the smaller the black hole, the smaller the impact.

But efforts to find extremely low-mass black holes have increased significantly in recent years, Thompson said, so we could soon learn much more about these mysterious objects.

"I think the field is pushing toward this, to really map out how many low-mass, how many intermediate-mass and how many high-mass black holes there are, because every time you find one it gives you a clue about which stars collapse, which explode and which are in between," he said in the statement.

"Very few such super-lightweight black holes are known, because they're incredibly hard to find"

Image source: Getty Images



# COULD LIFE EXIST AROUND BLACK HOLES?

They warp time and space, but could they also nurture life?

Reported by Nigel Watson

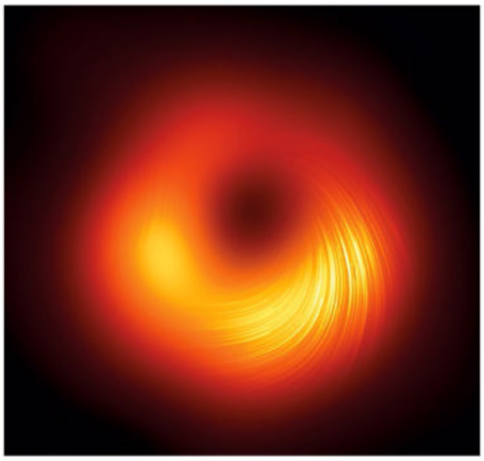
© Nicholas Forder

From the coldest to the hottest regions, life on Earth has filled every conceivable ecological niche. It's very likely life has evolved elsewhere, though despite our best efforts we haven't seen any signs of it yet. What is truly amazing is that scientists have speculated that life could exist on planets in the neighbourhood of black holes.

Black holes are the most extreme and awe-inspiring objects in the universe. At the centre of virtually every galaxy, including our own Milky Way, resides a menacing black hole that greedily consumes everything that falls into it – from vast dust clouds and planets to whole solar systems.

In the early evolution of galaxy formation, stellar material spinning around black holes formed flattened accretion discs billions of times the mass of our Sun, and great jets of gas fired out from them. These jets are like powerful beacons, 1,000 times brighter than our Milky Way, and are known as quasars. Much of the gas that fuelled quasars has run out in mature galaxies, but quasars can still be observed in very distant young galaxies.

The black hole itself is formed when a massive star has exhausted all its hydrogen and helium gases, causing it to violently explode and triggering its inner core to collapse in on itself. The outermost region of the black hole is the event horizon, and beyond that point the escape velocity to get out of the hole's gravitational pull is greater than the speed of light. Therefore nothing can escape this point of infinite density, known as the singularity.

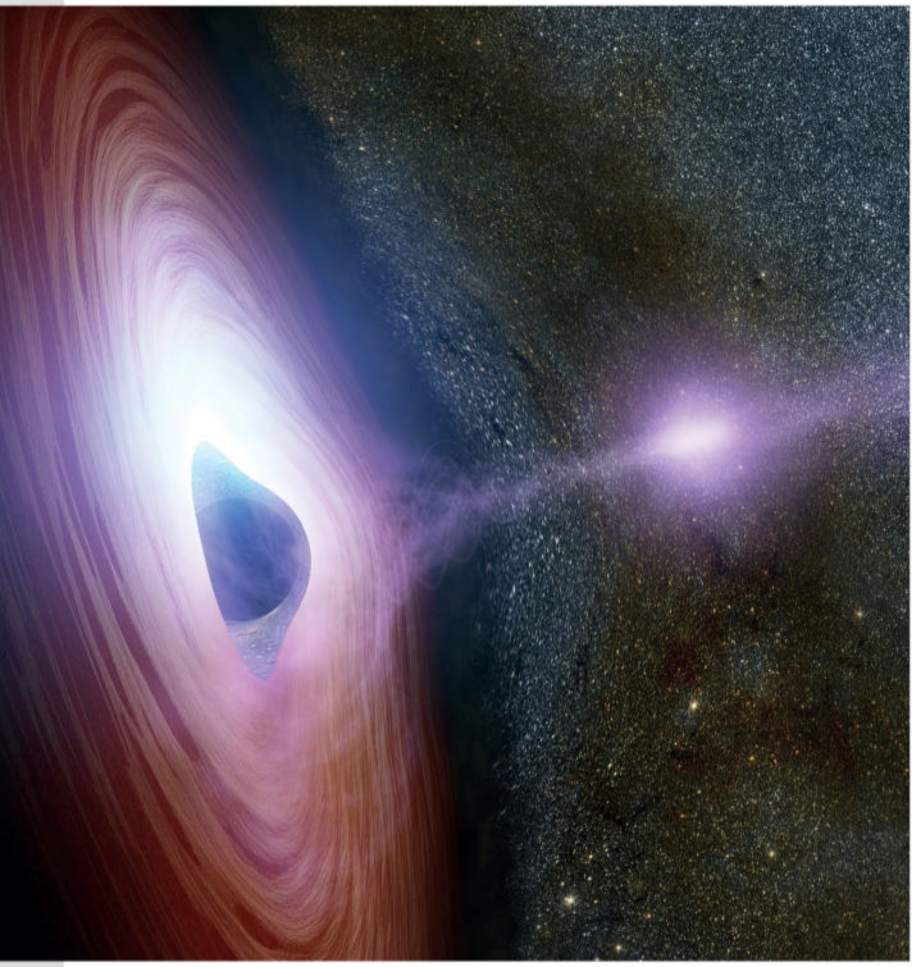


© NASA

## What would the planets be like?

The dust particles orbiting black holes could form rocky 'blanets' ten times larger than Earth, or create gas giants. Such planets are more likely around cooler and dimmer supermassive black holes, where essential planet-building ice-covered dust particles might exist.

Such blanets, or planets captured by a black hole's gravity, would be orbiting at least ten light years from the black hole, otherwise they would be in danger of being sucked into it, or its gravitational forces might strip away their planetary atmosphere. They would also be subjected to high levels of ultraviolet light and X-ray radiation.



© NASA

**Above:** A polarised image of the magnetic fields spinning around a black hole, released in March 2021, using data from radio telescopes around the world

**Left:** An artist's concept of a corona flare of energetic particles shooting out from a supermassive black hole

If you do fall into a black hole it is a gruesome experience, as the intense gravitational field of the singularity will pull you into a long, thin strand. This process is rather aptly called spaghettification. Any object can be spaghettified, including entire stars.

The chance of a life-supporting black hole planet seems impossible, but scientists are never one to shirk a challenge. A big boost to such speculation was the fictional Miller's planet in Christopher Nolan's 2014 film *Interstellar*. This was mainly because it used advice from theoretical physicist Dr Kip Thorne about the properties of wormholes and black holes. Although the science was praised, it was thought a planet so close to a black hole, with the time-dilation effects shown, would easily be blasted with lethal radiation and would be in serious danger of being drawn into the hole.

A group of astrophysicists led by Pavel Bakala of the Silesian University in Opava decided to take another look at this problem. Considering the thermodynamics of the situation, they postulated that the black hole would act as a heat sink for unusable waste heat – equivalent to the cold of space surrounding Earth. The usable energy would come from the cosmic microwave background (CMB) rather than a star like our Sun.

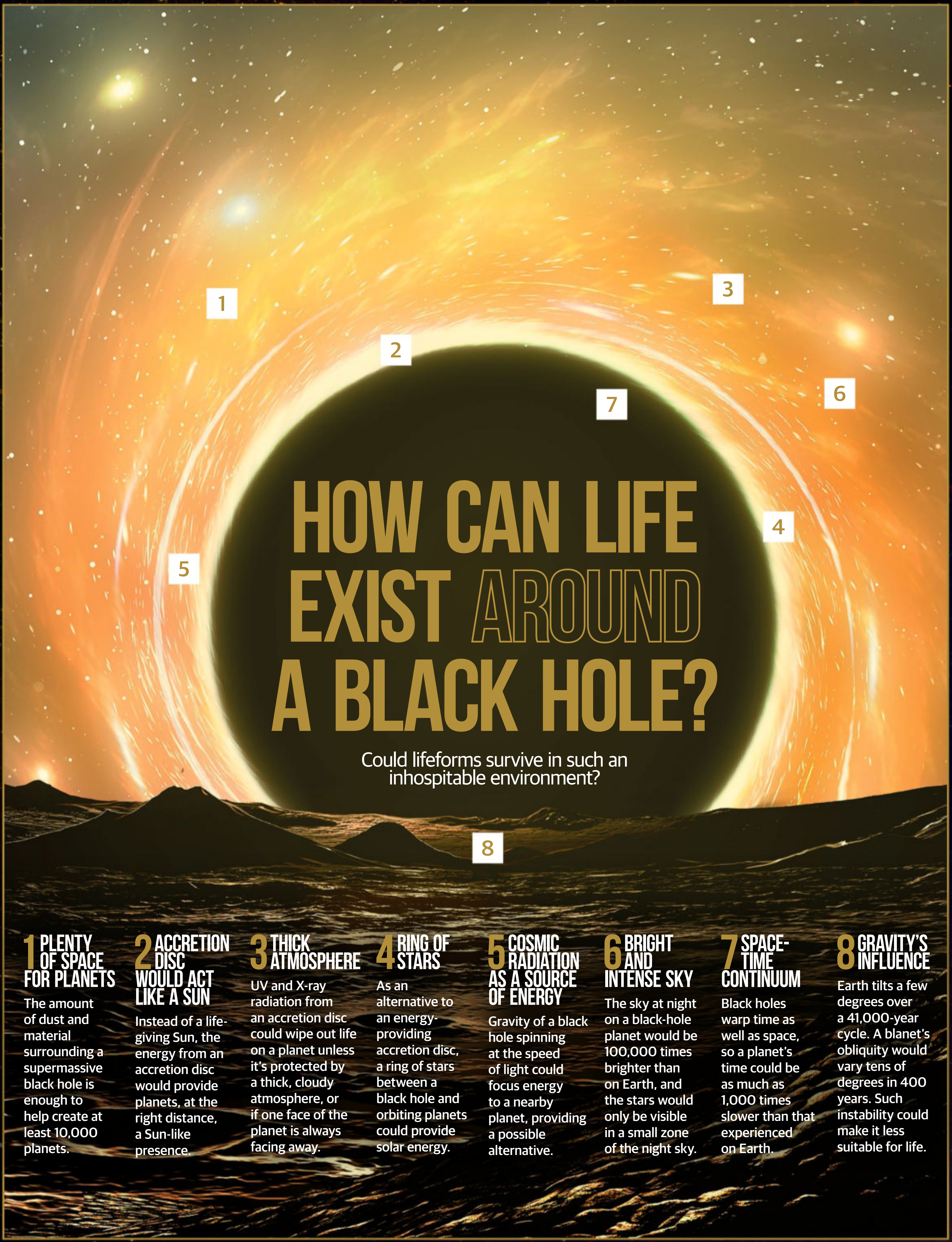
The CMB as a source of energy does not sound very promising, as it is relatively weak, but a supermassive black hole could compress and funnel it into optical wavelengths. Its narrow beam of light would look like a bright star near the shadow of the black hole to an observer on a nearby planet.

Four years after putting forward that idea, the team refined it to account for the weakness of the CMB. This could be catered for if the planet is in an orbit close to the black hole, the danger of course being that it might be drawn into its singularity. To avoid this they calculated that a planet would be able to be in a close, stable orbit with strong enough CMB light if the black hole spun at a 100 millionth less than the speed of light.

The black hole in our Milky Way, although having a mass around 4 million times larger than the Sun, would be too small, and would rip apart any nearby planet. For a planet to evade that fate it would have to orbit a supermassive black hole that only rips up planets when they go beyond its event horizon. Such black holes would have to have a mass of at least 163 million times that of our Sun.

Another consideration is that the black hole would need to be in a fairly old galaxy, with plenty of empty space around it. Otherwise any matter in the area that is sucked into the black hole would blast out deadly radiation as it spirals to certain doom inside the singularity.

Instead of the weak CMB, the energy from the accretion disc surrounding a black hole could be an alternative. Jeremy Schnittman, a research astrophysicist at NASA's Goddard Space Flight Center, who was also inspired by *Interstellar*, has considered that the bright, hot gas from the accretion disc could provide the energy and light to sustain life forms. That's the good news, but he also believes that the nearby influence of a black hole would amplify and intensify ultraviolet rays to such an extent that it would wipe out any life.



# HOW CAN LIFE EXIST AROUND A BLACK HOLE?

Could lifeforms survive in such an inhospitable environment?

### 1 PLENTY OF SPACE FOR PLANETS

The amount of dust and material surrounding a supermassive black hole is enough to help create at least 10,000 planets.

### 2 ACCRETION DISC WOULD ACT LIKE A SUN

Instead of a life-giving Sun, the energy from an accretion disc would provide planets, at the right distance, a Sun-like presence.

### 3 THICK ATMOSPHERE

UV and X-ray radiation from an accretion disc could wipe out life on a planet unless it's protected by a thick, cloudy atmosphere, or if one face of the planet is always facing away.

### 4 RING OF STARS

As an alternative to an energy-providing accretion disc, a ring of stars between a black hole and orbiting planets could provide solar energy.

### 5 COSMIC RADIATION AS A SOURCE OF ENERGY

Gravity of a black hole spinning at the speed of light could focus energy to a nearby planet, providing a possible alternative.

### 6 BRIGHT AND INTENSE SKY

The sky at night on a black-hole planet would be 100,000 times brighter than on Earth, and the stars would only be visible in a small zone of the night sky.

### 7 SPACE-TIME CONTINUUM

Black holes warp time as well as space, so a planet's time could be as much as 1,000 times slower than that experienced on Earth.

### 8 GRAVITY'S INFLUENCE

Earth tilts a few degrees over a 41,000-year cycle. A blanet's obliquity would vary tens of degrees in 400 years. Such instability could make it less suitable for life.

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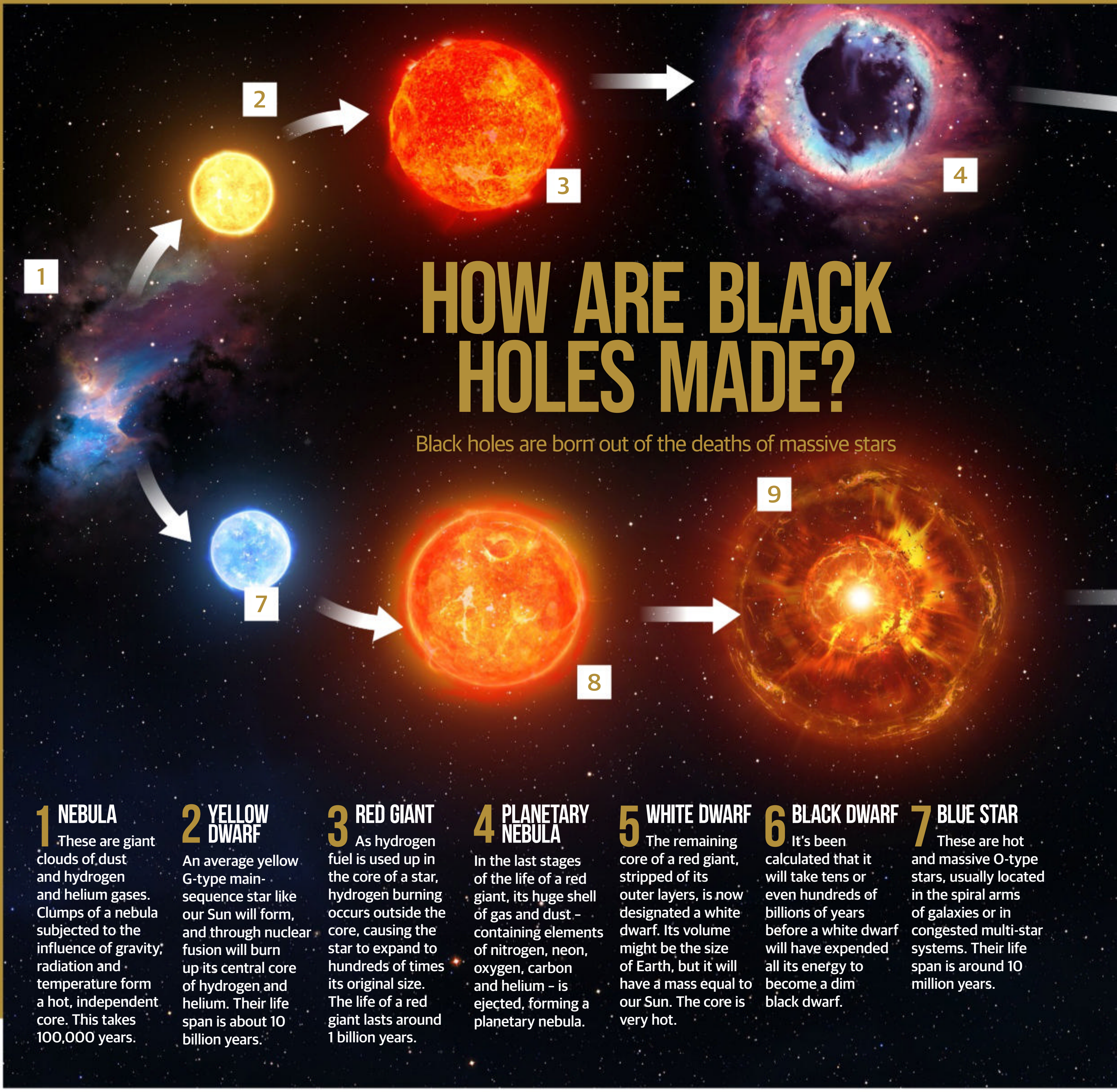

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# HOW ARE BLACK HOLES MADE?

Black holes are born out of the deaths of massive stars

### 1 NEBULA

These are giant clouds of dust and hydrogen and helium gases. Clumps of a nebula subjected to the influence of gravity, radiation and temperature form a hot, independent core. This takes 100,000 years.

### 2 YELLOW DWARF

An average yellow G-type main-sequence star like our Sun will form, and through nuclear fusion will burn up its central core of hydrogen and helium. Their life span is about 10 billion years.

### 3 RED GIANT

As hydrogen fuel is used up in the core of a star, hydrogen burning occurs outside the core, causing the star to expand to hundreds of times its original size. The life of a red giant lasts around 1 billion years.

### 4 PLANETARY NEBULA

In the last stages of the life of a red giant, its huge shell of gas and dust – containing elements of nitrogen, neon, oxygen, carbon and helium – is ejected, forming a planetary nebula.

### 5 WHITE DWARF

The remaining core of a red giant, stripped of its outer layers, is now designated a white dwarf. Its volume might be the size of Earth, but it will have a mass equal to our Sun. The core is very hot.

### 6 BLACK DWARF

It's been calculated that it will take tens or even hundreds of billions of years before a white dwarf will have expended all its energy to become a dim black dwarf.

### 7 BLUE STAR

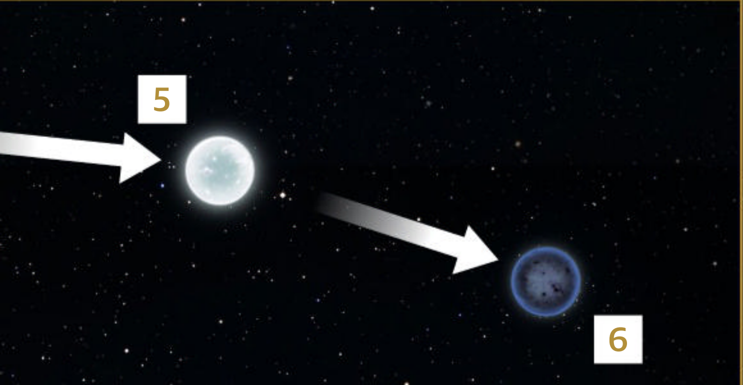
These are hot and massive O-type stars, usually located in the spiral arms of galaxies or in congested multi-star systems. Their life span is around 10 million years.

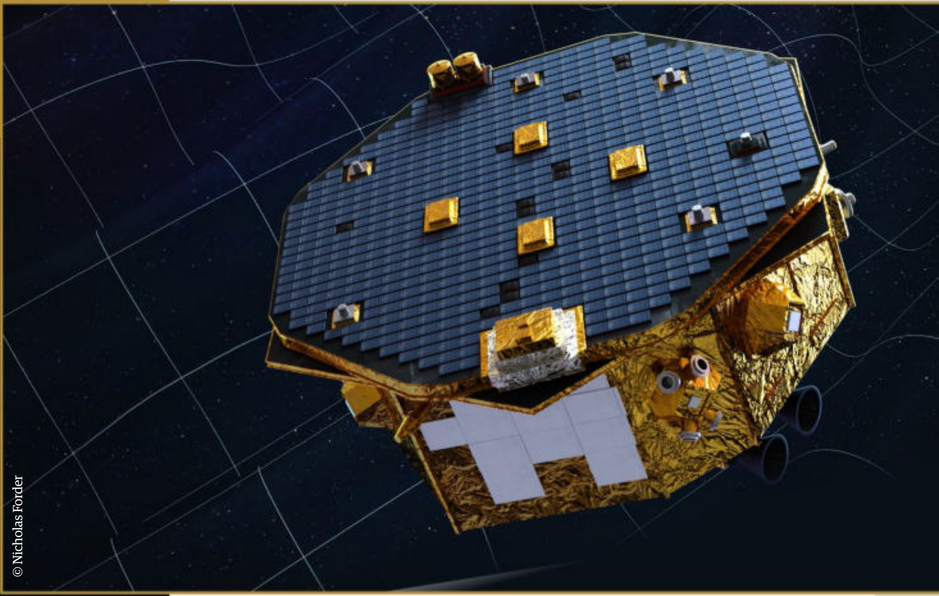
Keiichi Wada of Kagoshima University, Japan, and his team note that more distant and relatively safe zones around supermassive black holes could be inhabited by planets and stars captured by its powerful gravitational forces. From there they speculate that dust particles and gasses in the same zone could be pulled together to create new planets that they have termed 'blanets', short for black hole planets.

There are several factors that condition the formation of a blanet. One is that the dust and rocks could smash themselves apart rather than clump together. To help with clumping, ice-covered dust particles are required. Given the right conditions, they calculate that at a distance of 13 light years from a black hole with a mass 1 million times that of our Sun, blanets could grow from 20 to 3,000 times the mass of Earth over a period of about 80 million years.

Much depends on the mass of the black hole and the distance from it. For a black hole with a mass 10 million times our Sun's, blanets could become as massive as gas giants or stars. The team certainly agrees that blanets would be very different from the type of planets formed in solar systems like our own. It might also take equally different types of life to evolve in what we would regard as a very inhospitable environment. Sean N Raymond, at the Observatory of Bordeaux in France, notes: "What does life need? If we're shooting for Earth-like life, then it would need a rocky planet, liquid water and the right amount of energy. Too much energy would strip a planet's atmosphere and surface water; too little would leave the surface frozen over.

"Planets have actually been found around neutron stars, so it's reasonable to expect them to survive around solar-mass black holes. Could such planets form with water? That's a big 'who knows?' I think it's plausible to imagine that water could

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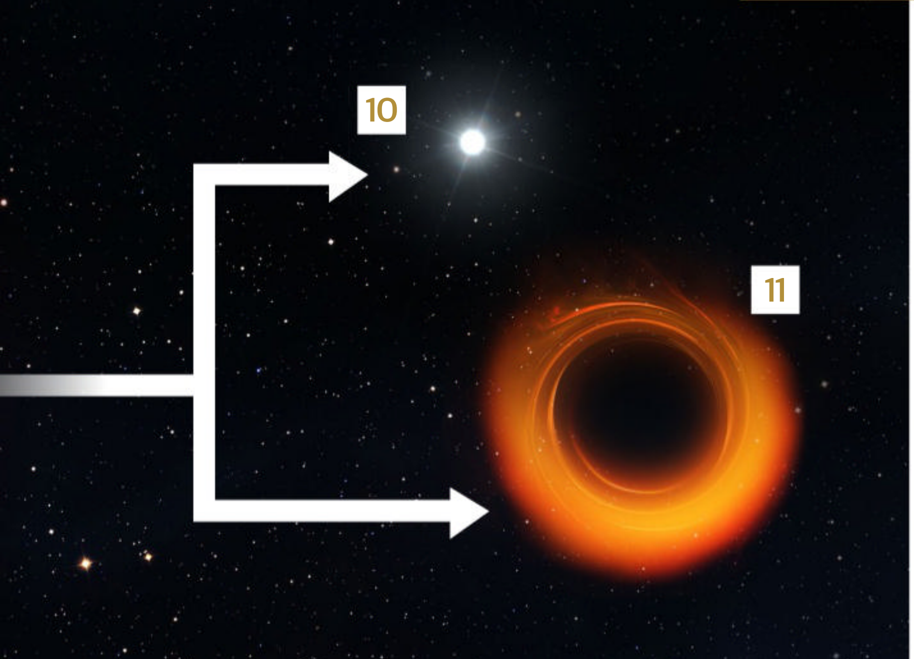


### 8 RED SUPERGIANT

As the hydrogen and helium at the core are burnt off in large stars – those 10 to 40 times the size of our Sun – outer layers expand at a rapid rate. They have a life span of a few million years.

### 9 SUPERNOVA

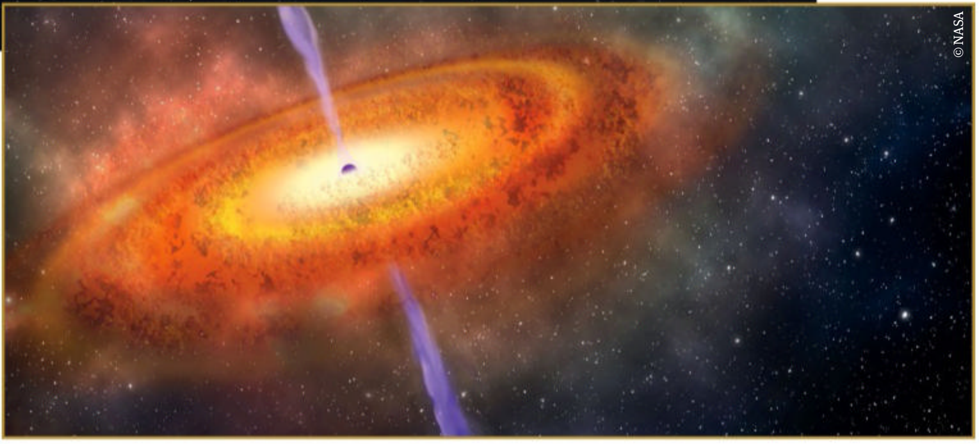
This is the gigantic explosion caused when a supergiant runs out of fuel. Within a few seconds the mass is crushed towards its core, resulting in shock waves that trigger the explosion of its outer layers.

### 10 NEUTRON STAR

A neutron star is incredibly dense – gravity is an astonishing 200 billion times that of Earth's. One tablespoon of a neutron star is equivalent to the weight of Everest.

### 11 BLACK HOLE

The explosive power of a supernova can produce a black hole at its core. Its gravity is so powerful that even light cannot escape it, and it distorts the space-time continuum with its immense mass.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**Above:** The Laser Interferometer Space Antenna will launch in 2034, able to detect tiny ripples caused by black holes colliding, called gravitational waves

**Below:** An artist's impression of a supermassive black hole 800 million times the mass of the Sun, with quasar jets blasting away from it

> "Planets have been found around neutron stars, so it's reasonable to expect them to survive" **Sean Raymond**

end up on a planet around a black hole, simply because water is so abundant in the universe. But the exact mechanisms at play have not been studied in great detail," Raymond explains.

"Supermassive black holes are known to have accretion discs. These are extremely luminous, which is really not a problem for life – the 'habitable zone' would simply be moved farther from the black hole. What may be problematic is that the radiation from black hole accretion discs can be very 'hard', with a lot of energy being emitted at very high-energy wavelengths. High-energy radiation can strip planetary atmospheres and water – not great for life.

"If we take the worst case scenario of a planet completely bathed in high-energy radiation, is it hopeless for life? Probably, but you can easily imagine localised habitable regions," he continues. "For instance, if the planet is tidally locked to the black hole, then the dark side of the planet may be more hospitable to life. Even without tidal locking, subsurface water could presumably exist for long timescales, as it might still exist on Mars today. Or volcanic hot spots could provide a trickle of atmosphere and water…"

As a thought experiment, Raymond considers that 550 Earth-sized planets could orbit in the habitable zone of a supermassive black hole. In comparison, only six Earth-sized planets would be able to stay in stable orbits within the habitable zone of our Sun.

The hypothetical black hole would have a million times more mass than the Sun, and its gravity would pull at the planets, moving them out of the habitable zone. To keep them in the habitable zone in stable, concentric orbits, a ring of nine Sun-like stars would need to be between the black hole and the planets. The stars would take three hours to orbit the black hole, and the planets would orbit it in a range of 1.6 to 4.6 days.

Abraham 'Avi' Loeb of Harvard University has also stretched his imagination by considering the numerous benefits of living near a supermassive black hole. This includes using the accretion disc as the ultimate garbage-disposal system – one that would produce radiation from the waste to provide a source of energy.

The immensely powerful jets of energy sent out by the black hole could power a spacecraft with a lightsail close to the speed of light. For the more adventurous, you could ride on a planet at the speed of light powered by the gravitational forces generated when two black holes merge together.

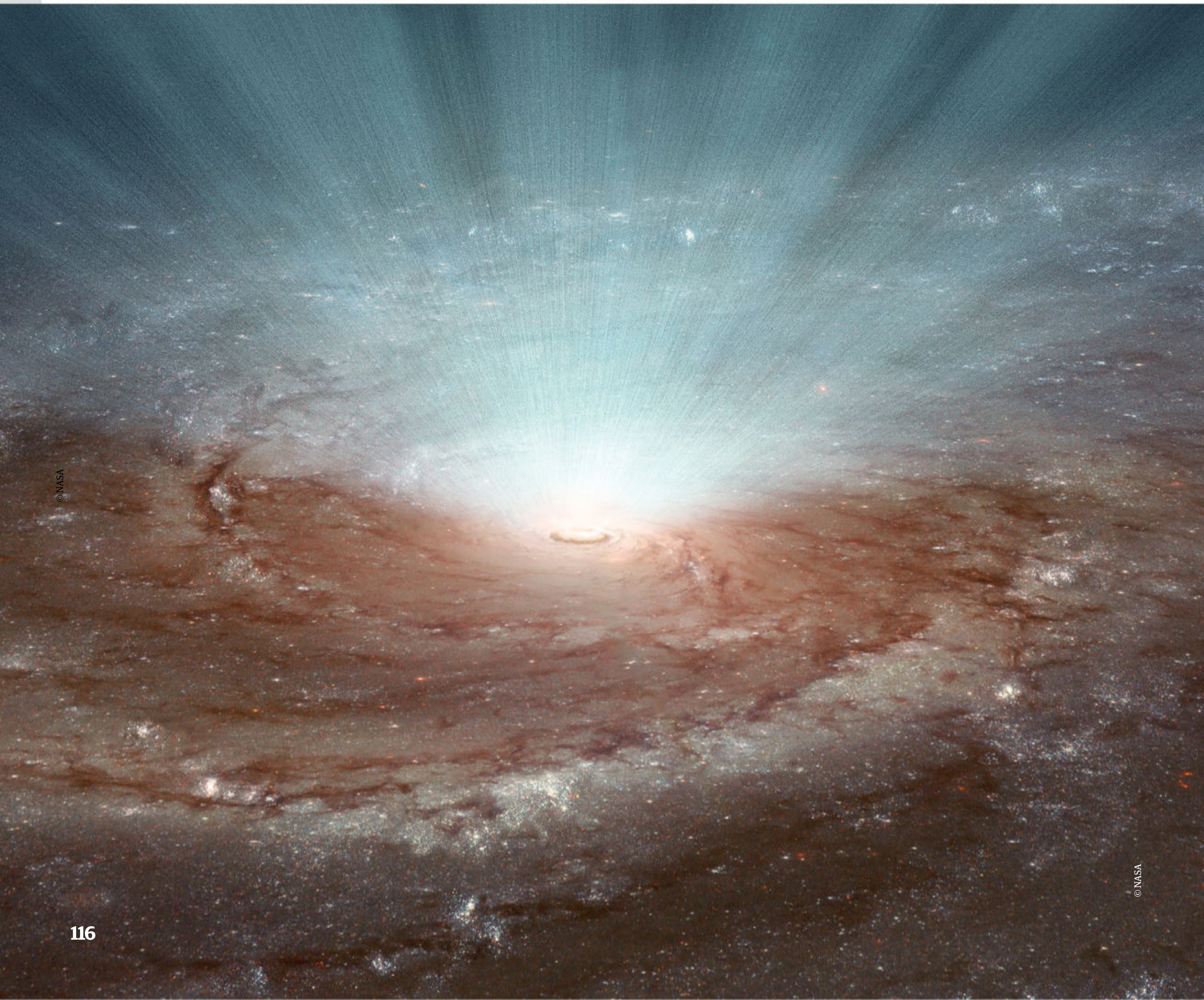
In his essay *Shooting Stars at the Speed of Light*, Loeb notes: "All in all galactic nuclei offer launching sites for the fastest habitable platforms that nature offers for free. It would not be surprising if advanced technological civilisations choose to migrate towards galactic centres for the same reason that astronauts and spectators flock to Cape Canaveral during rocket launches. With that perspective in mind, the Search for Extraterrestrial Intelligence (SETI) should check for radio signals coming from riders of hypervelocity stars."

Given all the dangers a black hole presents, it's difficult to know how a habitable planet could exist against all these odds. Any life form would have to deal with the high levels of radiation, too much or too few suitable sources of light and energy, the erratic bursts of radiation from the black hole's accretion disc, space debris, an unstable and unsustainable orbit and the effects of time dilation.

Perhaps only primitive life might evolve on such planets, or fast evolving and very adaptable intelligent species might exist on them. Raymond offers some hope: "I would expect life to be harsher on planets around black holes, but I think that seeing them as necessarily barren, inhospitable worlds is a failure of imagination."

**Nigel Watson**
*Space science writer*
Nigel has written extensively about science and technology, in particular about extraterrestrial contact. He is the author of four books on alien life.

**Above:** Rendition of the accretion discs of two supermassive black holes interacting
**Below:** An artistic view of findings that indicate black holes can blast out vast amounts of matter in all directions



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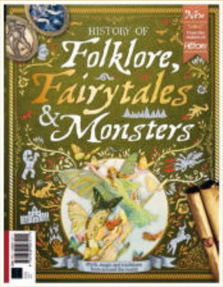
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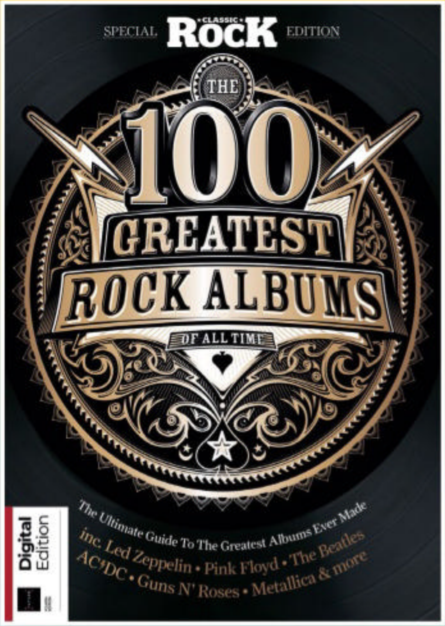
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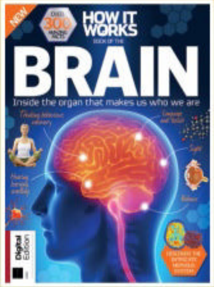
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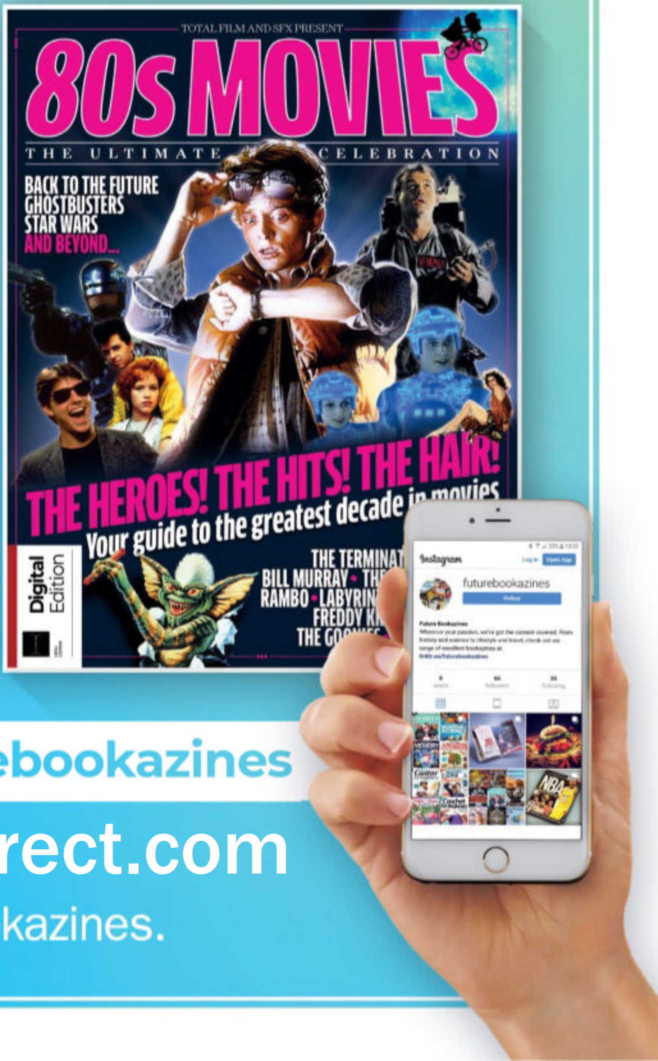
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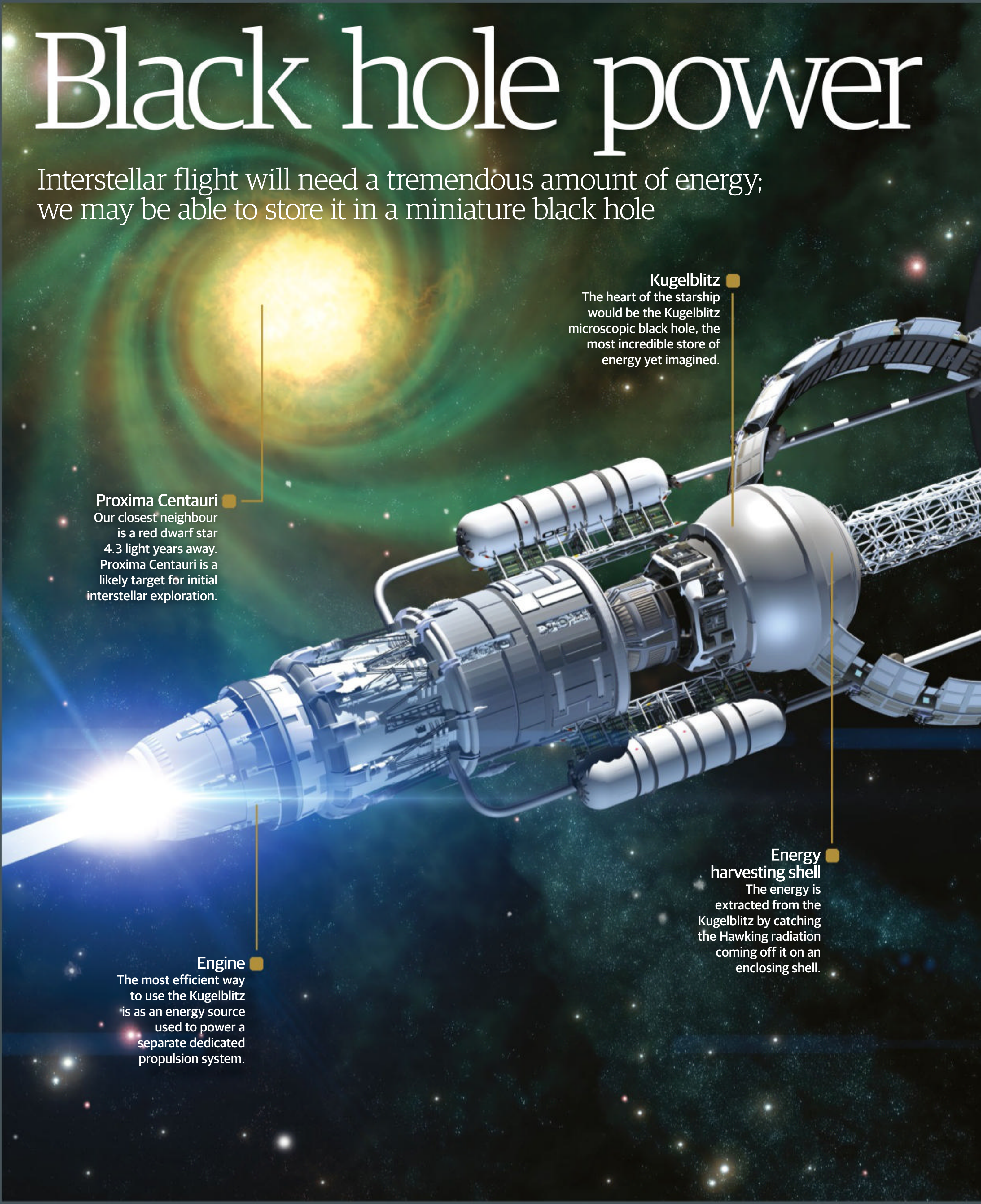
# Black hole power

Interstellar flight will need a tremendous amount of energy; we may be able to store it in a miniature black hole

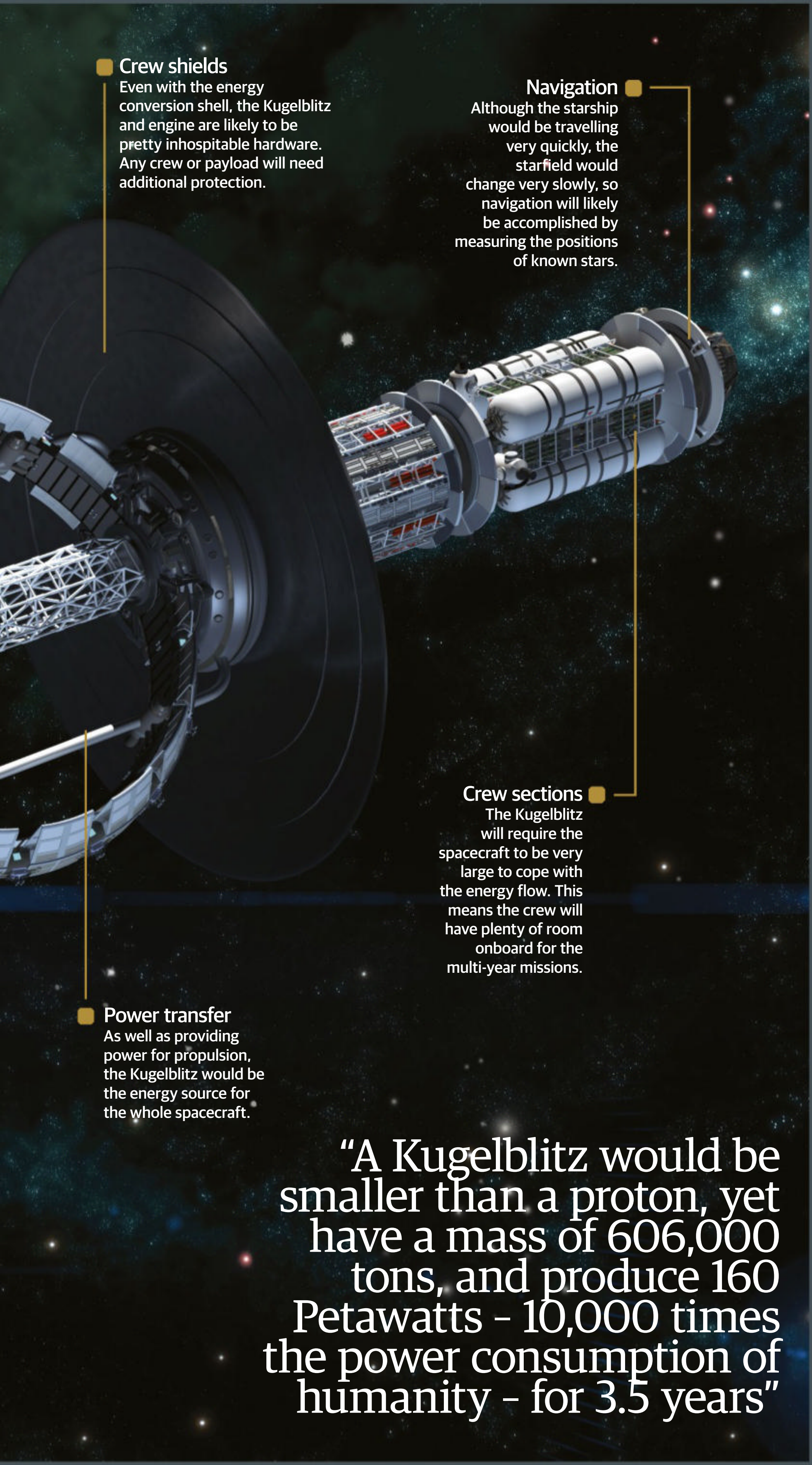


**Kugelblitz**
The heart of the starship would be the Kugelblitz microscopic black hole, the most incredible store of energy yet imagined.

**Proxima Centauri**
Our closest neighbour is a red dwarf star 4.3 light years away. Proxima Centauri is a likely target for initial interstellar exploration.

**Energy harvesting shell**
The energy is extracted from the Kugelblitz by catching the Hawking radiation coming off it on an enclosing shell.

**Engine**
The most efficient way to use the Kugelblitz is as an energy source used to power a separate dedicated propulsion system.



**Crew shields**
Even with the energy conversion shell, the Kugelblitz and engine are likely to be pretty inhospitable hardware. Any crew or payload will need additional protection.

**Navigation**
Although the starship would be travelling very quickly, the starfield would change very slowly, so navigation will likely be accomplished by measuring the positions of known stars.

**Crew sections**
The Kugelblitz will require the spacecraft to be very large to cope with the energy flow. This means the crew will have plenty of room onboard for the multi-year missions.

**Power transfer**
As well as providing power for propulsion, the Kugelblitz would be the energy source for the whole spacecraft.

> "A Kugelblitz would be smaller than a proton, yet have a mass of 606,000 tons, and produce 160 Petawatts - 10,000 times the power consumption of humanity - for 3.5 years"

Interstellar distances are difficult to conceive. Our nearest star is Proxima Centauri, a red dwarf 4.3 light years away. That's more than 266,000 times the distance from Earth to the Sun and if our fastest spacecraft, Voyager 1, which is flying at 18 kilometres (11 miles) per second, were headed that way, it would still take 80,000 years to get there. For humans to be able to explore the galaxy, we are going to need another way to travel, but while the focus has been on the propulsion side of the puzzle, equally challenging is how we power such journeys. But there's a concept that might solve both problems: the Schwarzschild Kugelblitz, a craft powered by a black hole.

To make interstellar journeys in a reasonable time, we will have to achieve a good per cent of the speed of light (300,000,000 metres or 984,252,000 feet per second). For every kilogram (2.2 pounds) of mass that makes up the composition of a spacecraft and its payload, when travelling at 99.9 per cent the speed of light it will have a kinetic energy more than six times that contained in the Tsar Bomba, the largest nuclear weapon ever detonated. All this energy must be safely stored in a form that can be built into a spacecraft, and supplied to the starship without destroying it.

Writing in 1955, American physicist John Wheeler proposed that if enough energy could be concentrated into a small space, the energy would form a microscopic black hole. He nicknamed this concept the Kugelblitz - meaning 'ball lightning' in German - and as a black hole is defined by being mass-energy squashed so that its gravity won't let light escape, compressed within the Schwarzschild radius, it has become known as the Schwarzschild Kugelblitz.

Counterintuitively, black holes actually produce radiation; it was first proposed by Stephen Hawking in 1974 that when quantum fluctuations happen next to the horizon of a black hole, it leads to the creation of two particles, but instead of the particles annihilating each other, one gets sucked into the black hole letting the other escape. Because of the conservation of energy, this process uses up energy from the black hole, and unless it sucks in more stuff, this Hawking radiation will eventually cause it to evaporate. This effect would be even more pronounced with a Kugelblitz micro-black hole, enabling us to extract energy from it.

A practical Kugelblitz will be a balancing act - it must be small enough that it makes enough Hawking radiation, light enough that a spacecraft carrying it can accelerate it, but big enough to last long enough to be useful. Such a Kugelblitz would be smaller than a proton, yet have a mass of 606,000 tons, and would produce 160 petawatts (over 10,000 times the power consumption of humanity) for 3.5 years.

The simplest option for using this power source would be to place it at the focus of a vast parabolic reflector and use this to make a beam of Hawking radiation to push the craft along. While this approach is simple, it wouldn't make good use of the Kugelblitz's power; it would only be able to reach four per cent of light speed before the Kugelblitz evaporated. A more challenging but efficient option would be to enclose the Kugelblitz in a spherical shell, capturing all of its energy and using this to drive a heat engine of some sort. Assuming 100 per cent energy efficiency, this could accelerate a craft to ten per cent of light speed in 20 days. The engineering challenges are huge, but the Kugelblitz is the most compact energy source ever conceived, even over anti-matter. Perhaps one day it will be powering humanity across the stars.

# DO BLACK HOLES LEAK INTO PARALLEL UNIVERSES?

Information entering one of these high-gravity objects might not be destroyed but oozing into another cosmos entirely

Written by Colin Stuart

Invisible, enigmatic and infuriating, black holes are astounding. Formed from the explosive deaths of the most massive stars, they push our very understanding of space and time to its limit. They are regions of such concentrated gravity that escaping from their clutches is impossible for those venturing too close. Once you've crossed the event horizon, you'd have to travel faster than the speed of light to escape but nothing can travel faster than the speed of light. Breach the event horizon and you're doomed to oblivion. What's more, you cannot hail anyone for help.

These monsters are so vexing because at various times they are both big and small. They start as the size of a star, where Einstein's general theory of relativity rules the roost. But, as the core of the dead star collapses to form the black hole, matter is concentrated down into an ever-smaller space. Eventually it moves into a realm dominated by the rules of the super-small - the weird and wonderful world of quantum physics.

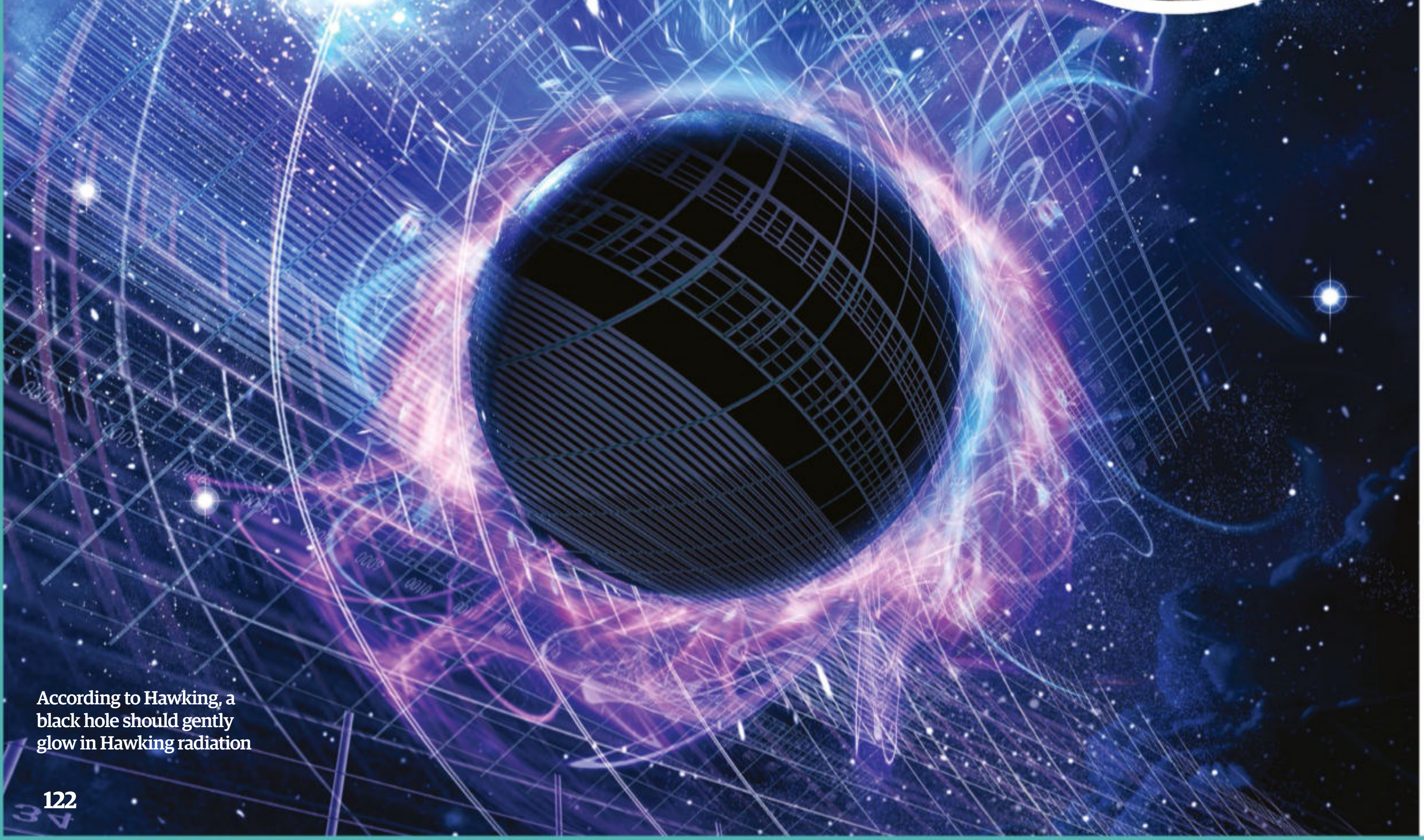
Both of these theories have rightly been lauded for their individual explanatory power. Einstein published his revolutionary theory in 1915 and so far it has passed every test thrown at it with flying colours. The recent discovery of the gravitational waves it predicted was a real triumph. Equally, our modern technological age is built on a thorough understanding of quantum physics. Yet physicists cannot get the two theories to play together nicely. There is no currently accepted theory of "quantum gravity" that combines the two neatly on the same scale. Black holes in particular embarrass us by confronting us with the reality of this dilemma.

One of the most famous attempts to reconcile the two theories with the physics of black holes was provided by Stephen Hawking in 1974. In a well-studied quantum phenomenon, a pair of subatomic particles can simultaneously pop into existence as long as they disappear again very quickly. Hawking imagined this happening right on the event horizon of a black hole. One particle is doomed, the other is free to escape. They can never be reunited, meaning a black hole must slowly lose energy to its immediate environment. According to Hawking, black holes evaporate over time in this way through the emission of one half of these particle pairs - an effect known as Hawking radiation.

However, that idea immediately threw up a problem because his calculations showed that the nature of Hawking radiation depends solely on the mass of the black hole. Yasunori Nomura, a researcher at the Berkeley Center for Theoretical Physics, likes to imagine throwing two books into the void. "One is Shakespeare, the other is Penthouse," he says. While both books contain different words, they both have exactly the same mass. As it only depends on the mass of the black hole, Nomura says the resulting Hawking radiation is identical in both cases. "It looks like the information about whether it was Shakespeare or Penthouse is completely lost," he says. Quantum

**Stephen Hawking was one of the first to successfully apply quantum physics to black holes**

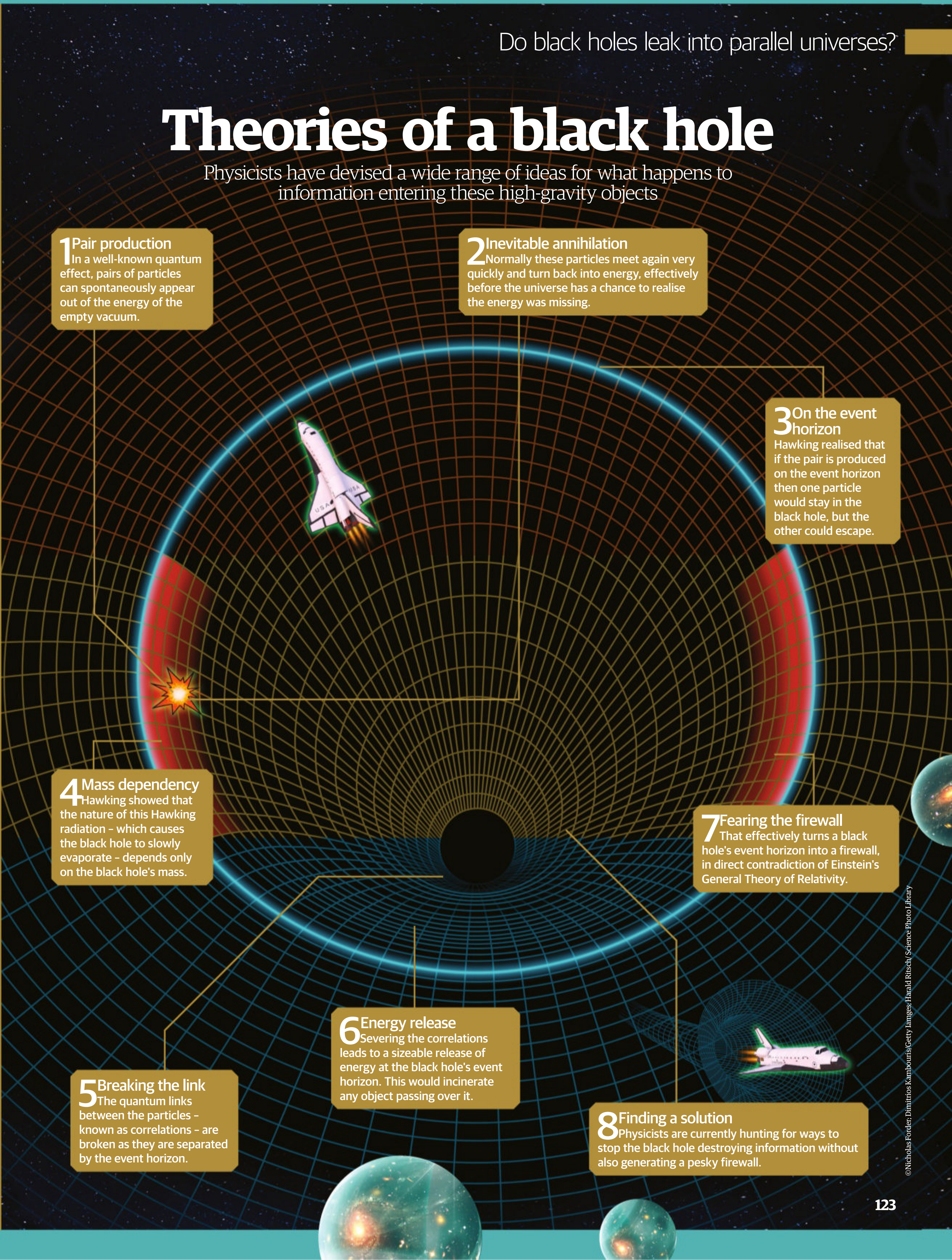
"A black hole can never completely evaporate away. Instead, a minuscule husk would always remain"



**According to Hawking, a black hole should gently glow in Hawking radiation**

# Theories of a black hole

Physicists have devised a wide range of ideas for what happens to information entering these high-gravity objects



**1 Pair production**
In a well-known quantum effect, pairs of particles can spontaneously appear out of the energy of the empty vacuum.

**2 Inevitable annihilation**
Normally these particles meet again very quickly and turn back into energy, effectively before the universe has a chance to realise the energy was missing.

**3 On the event horizon**
Hawking realised that if the pair is produced on the event horizon then one particle would stay in the black hole, but the other could escape.

**4 Mass dependency**
Hawking showed that the nature of this Hawking radiation – which causes the black hole to slowly evaporate – depends only on the black hole's mass.

**5 Breaking the link**
The quantum links between the particles – known as correlations – are broken as they are separated by the event horizon.

**6 Energy release**
Severing the correlations leads to a sizeable release of energy at the black hole's event horizon. This would incinerate any object passing over it.

**7 Fearing the firewall**
That effectively turns a black hole's event horizon into a firewall, in direct contradiction of Einstein's General Theory of Relativity.

**8 Finding a solution**
Physicists are currently hunting for ways to stop the black hole destroying information without also generating a pesky firewall.

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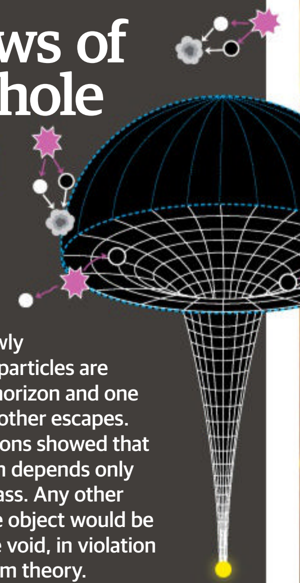
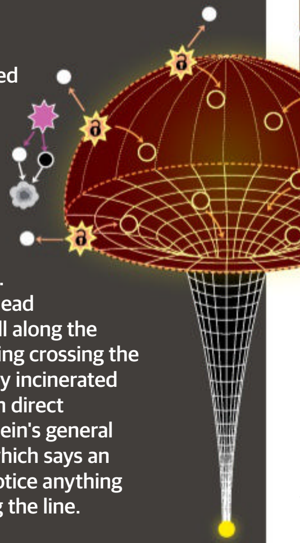
## Our views of a black hole



### Traditional view

Originally we thought nothing could escape from a black hole. Then, in 1974, Stephen Hawking argued that a black hole should slowly evaporate as pairs of particles are created at the event horizon and one is swallowed and the other escapes. However, his calculations showed that this Hawking radiation depends only on the black hole's mass. Any other information about the object would be completely lost to the void, in violation of the rules of quantum theory.

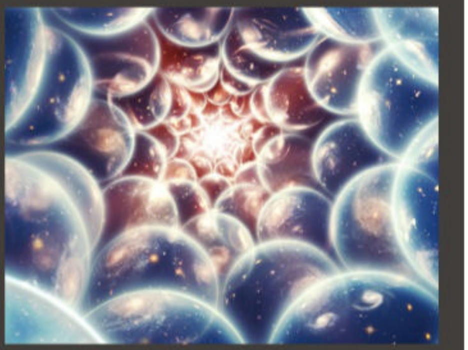


### Firewall view

Later, theorists realised that this 'information paradox' could be resolved if the quantum link between the two particles - a property called entanglement - is suddenly severed. However, this would lead to a spike in energy all along the event horizon. Anything crossing the line would be instantly incinerated in a 'firewall'. This is in direct contradiction to Einstein's general theory of relativity, which says an observer shouldn't notice anything special when crossing the line.

### Parallel universes view

Some physicists argue that both the information and firewall paradoxes go away if you think of black holes from the viewpoint of the Many Worlds interpretation of quantum theory. It says that every quantum event (such as the creation of a particle pair at the event horizon) splinters the universe into multiple copies - or branches - where all possible outcomes play out. Information is preserved across all branches and Einstein's rule about a smooth passage over the event horizon only applies to each individual branch.



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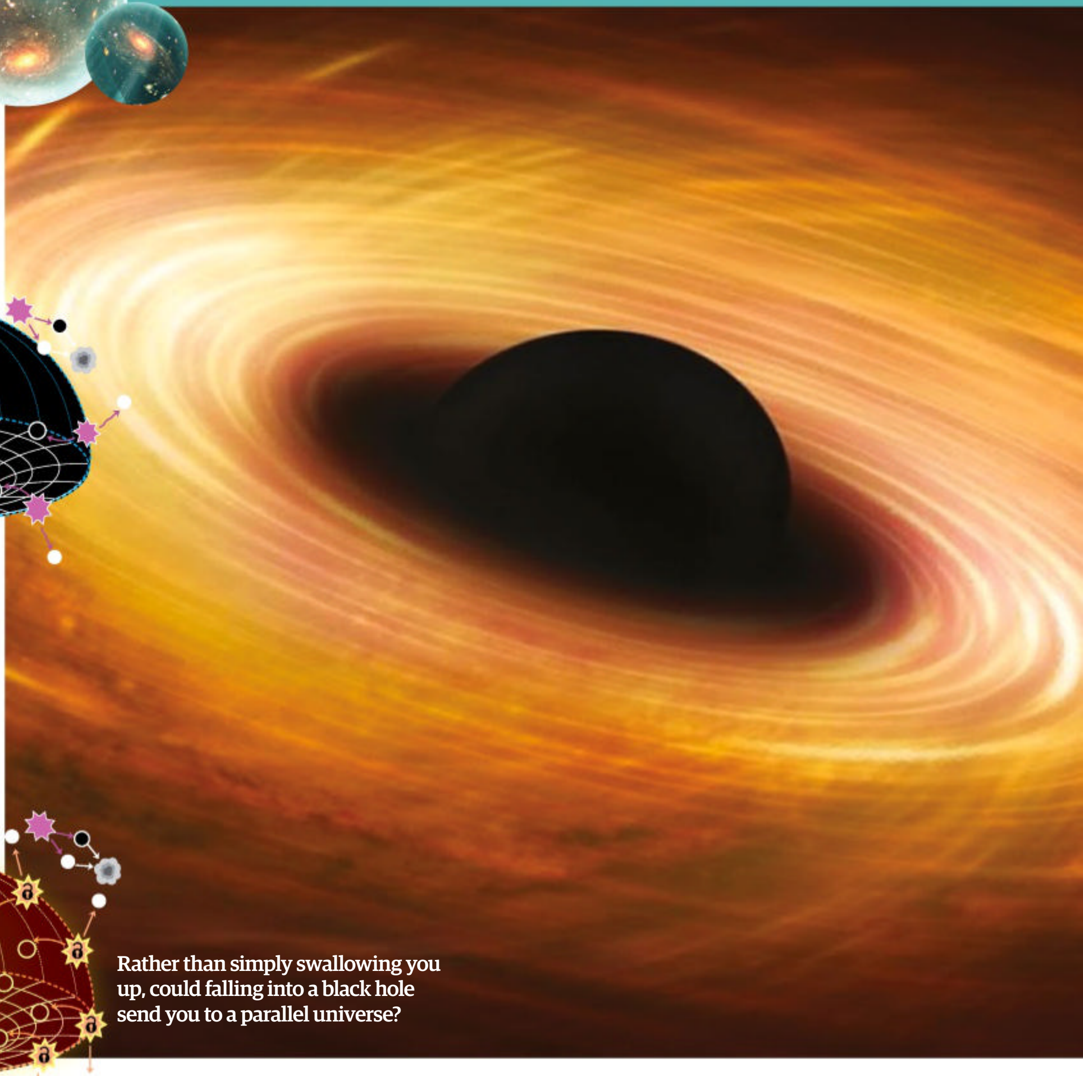


Rather than simply swallowing you up, could falling into a black hole send you to a parallel universe?

physics says that information cannot be created or destroyed. So where does the information go? This problem has become known as the 'Black Hole Information Paradox'.

Many physicists have wrestled with how to solve this thorny issue. In 2015, Hawking himself detailed a new idea, re-exploring the notion he'd had 40 years earlier. His radical solution to the information paradox is that the information contained within the two books never actually makes it into the black hole. "I propose that the information is stored not in the interior of the black hole as one might expect, but on its boundary, the event horizon," he said at a conference in Sweden on Hawking radiation held that year. According to Hawking, information about three-dimensional objects falling in ends up encoded as a two-dimensional hologram on the event horizon. Later, outgoing Hawking radiation re-delivers this information back into the universe. Given enough time, someone would, in principle, be able to recover the information contained within the books. Hawking would go on to tell the conference that black holes are not the eternal prisons they were once thought to be.

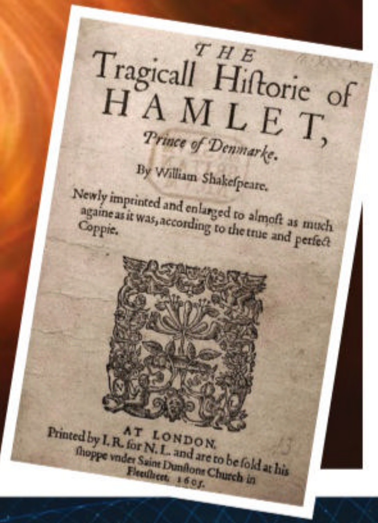
Nobel prize-winning physicist Gerard 't Hooft has another idea. An object crossing the event horizon will begin to feel dramatic changes in its gravitational field. Hawking radiation will be affected by these gravitational changes and so carry out with it information about what the incoming object was. However, both Hawking and 't Hooft's ideas have a significant snag: quantum physics not only forbids information from being destroyed, it also outlaws it being duplicated. The object falling in will carry one copy of its information, while another either sits as a hologram on the event horizon or is carried outwards by Hawking radiation. The mystery is far from solved.

Other researchers found a less drastic ray of hope when they discovered a way that Hawking radiation might preserve the information contained within objects added to the black hole without the need for holograms or duplicates. However, they could only get this to happen by dramatically severing the quantum link between the two particles that initially created the Hawking radiation. Cutting the cord would lead to a sudden burst of energy. With this process happening all along the event horizon, crossing over it would be like entering hell. You'd soon be incinerated by what physicists have a dubbed a 'firewall'.

This creates a new paradox. Einstein's general theory of relativity forbids anything special happening when you cross over the event horizon. Like the Earth's equator, it is a purely mathematical line. Why should you be set alight just because you

> "The information is stored not in the interior of the black hole, but on its boundary, the event horizon" **Stephen Hawking**

Gerard 't Hooft thinks the gravity of infalling objects imprints a black hole's Hawking radiation



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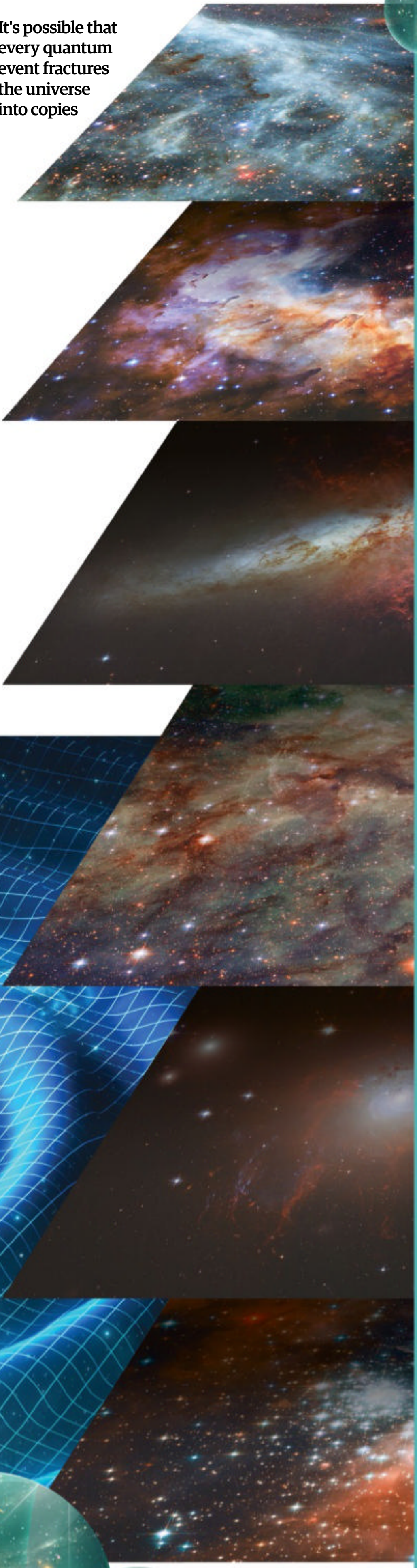
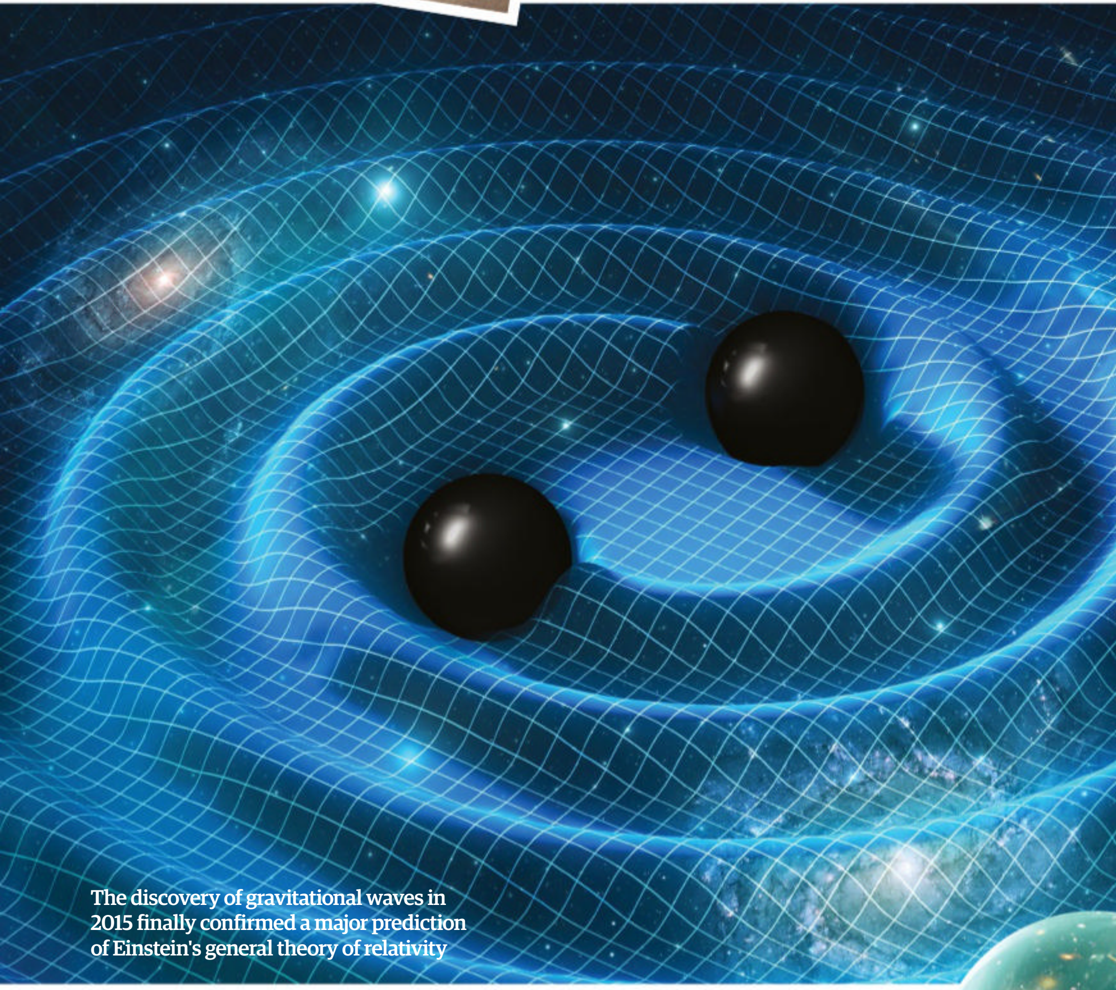
pass from the equivalent of one hemisphere into another? Physicists call this the Firewall Paradox. Applying quantum physics to black holes suggests the existence of Hawking radiation. At first that implied information can be destroyed - the Information Paradox - unless crossing the event horizon singes you into a ball of smoke - the Firewall Paradox.

"I'm just not comfortable with this idea," says Ana Alonso-Serrano at the Max Planck Institute for Gravitational Physics in Germany. She's been looking for an alternative way out and now believes she may have found one. "You don't need a firewall," she says. To come to this conclusion, Alonso-Serrano looked at some of the current models for how quantum gravity might work. She specifically investigated something called the Generalised Uncertainty Principle (GUP), which says the more you know about a black hole's size the less you know about its energy. Her work shows that more and more Hawking radiation would be given off as the black hole evaporates, changing the amount of information it carries away. "Information isn't lost - it is hidden in the Hawking radiation," she says.

Alonso-Serrano admits that her solution "is not a complete resolution" to the problem, but it has the potential to eliminate the pesky firewall. Her work also shows that a black hole can never completely evaporate away. Instead, a minuscule husk would always remain.



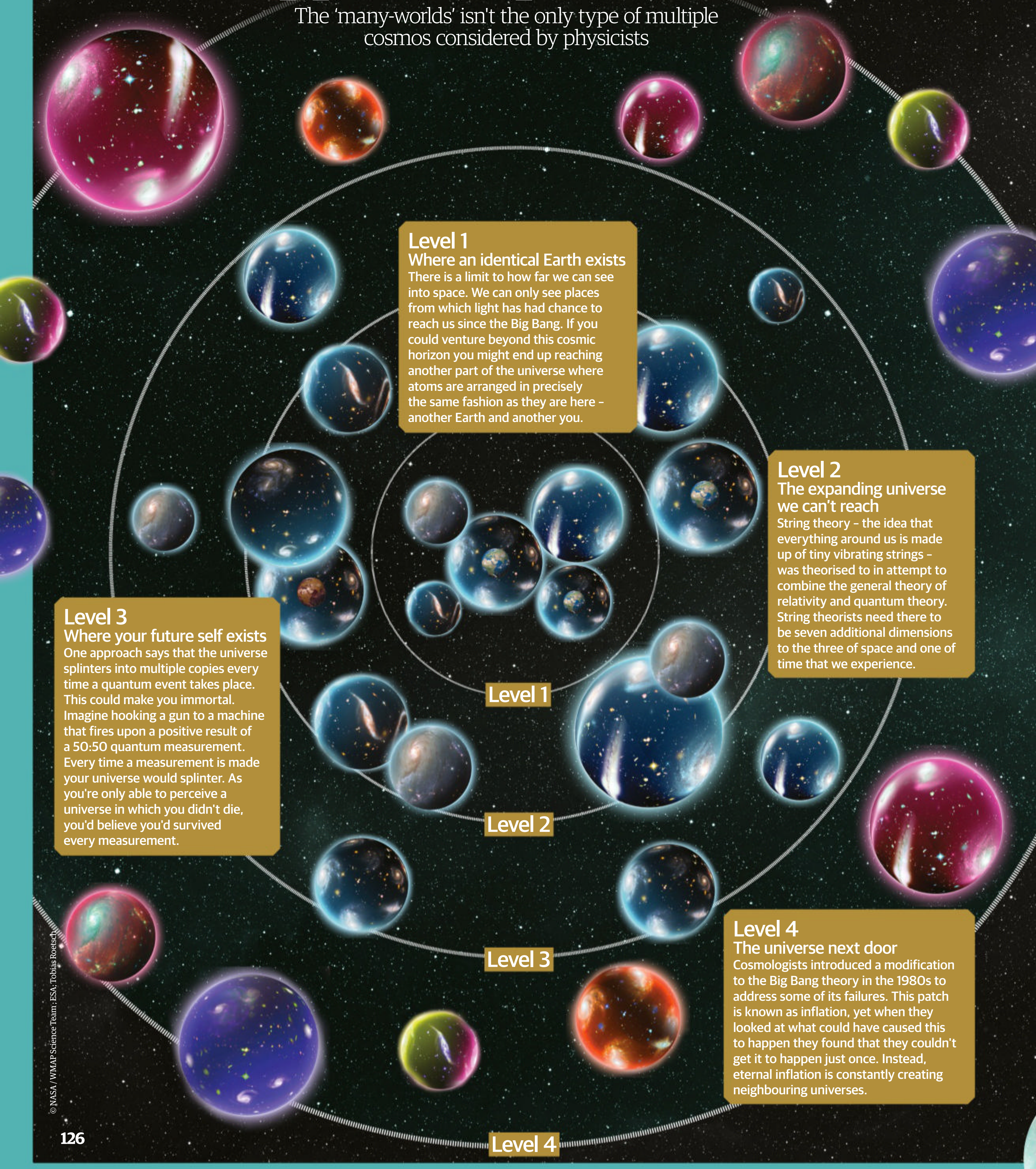
It's possible that every quantum event fractures the universe into copies



The discovery of gravitational waves in 2015 finally confirmed a major prediction of Einstein's general theory of relativity

# What happens in parallel universes?

The 'many-worlds' isn't the only type of multiple cosmos considered by physicists



## Level 1
### Where an identical Earth exists

There is a limit to how far we can see into space. We can only see places from which light has had chance to reach us since the Big Bang. If you could venture beyond this cosmic horizon you might end up reaching another part of the universe where atoms are arranged in precisely the same fashion as they are here – another Earth and another you.

## Level 2
### The expanding universe we can't reach

String theory – the idea that everything around us is made up of tiny vibrating strings – was theorised to in attempt to combine the general theory of relativity and quantum theory. String theorists need there to be seven additional dimensions to the three of space and one of time that we experience.

## Level 3
### Where your future self exists

One approach says that the universe splinters into multiple copies every time a quantum event takes place. This could make you immortal. Imagine hooking a gun to a machine that fires upon a positive result of a 50:50 quantum measurement. Every time a measurement is made your universe would splinter. As you're only able to perceive a universe in which you didn't die, you'd believe you'd survived every measurement.

## Level 4
### The universe next door

Cosmologists introduced a modification to the Big Bang theory in the 1980s to address some of its failures. This patch is known as inflation, yet when they looked at what could have caused this to happen they found that they couldn't get it to happen just once. Instead, eternal inflation is constantly creating neighbouring universes.

© NASA / WMAP Science Team; ESA; Tobias Roetsch

**Danish physicist Niels Bohr was instrumental in developing the Copenhagen interpretation of quantum theory**

Aidan Chatwin-Davies, from Caltech in California, is another theoretical physicist not fond of firewalls. He has recently found an alternative way to abandon a blazing event horizon. He says all we have to do is think of black holes in terms of the many worlds interpretation of quantum physics – an idea first devised by physicist Hugh Everett in the 1950s as an alternative way of thinking about the weird sub-atomic world.

Quantum physics famously says that a particle can be in two places at once, or in two different states simultaneously. The original interpretation of this idea, favoured by Niels Bohr and devised in Denmark, is known as the Copenhagen interpretation. It argues that only once the particle is measured does it 'decide' which state to appear in.

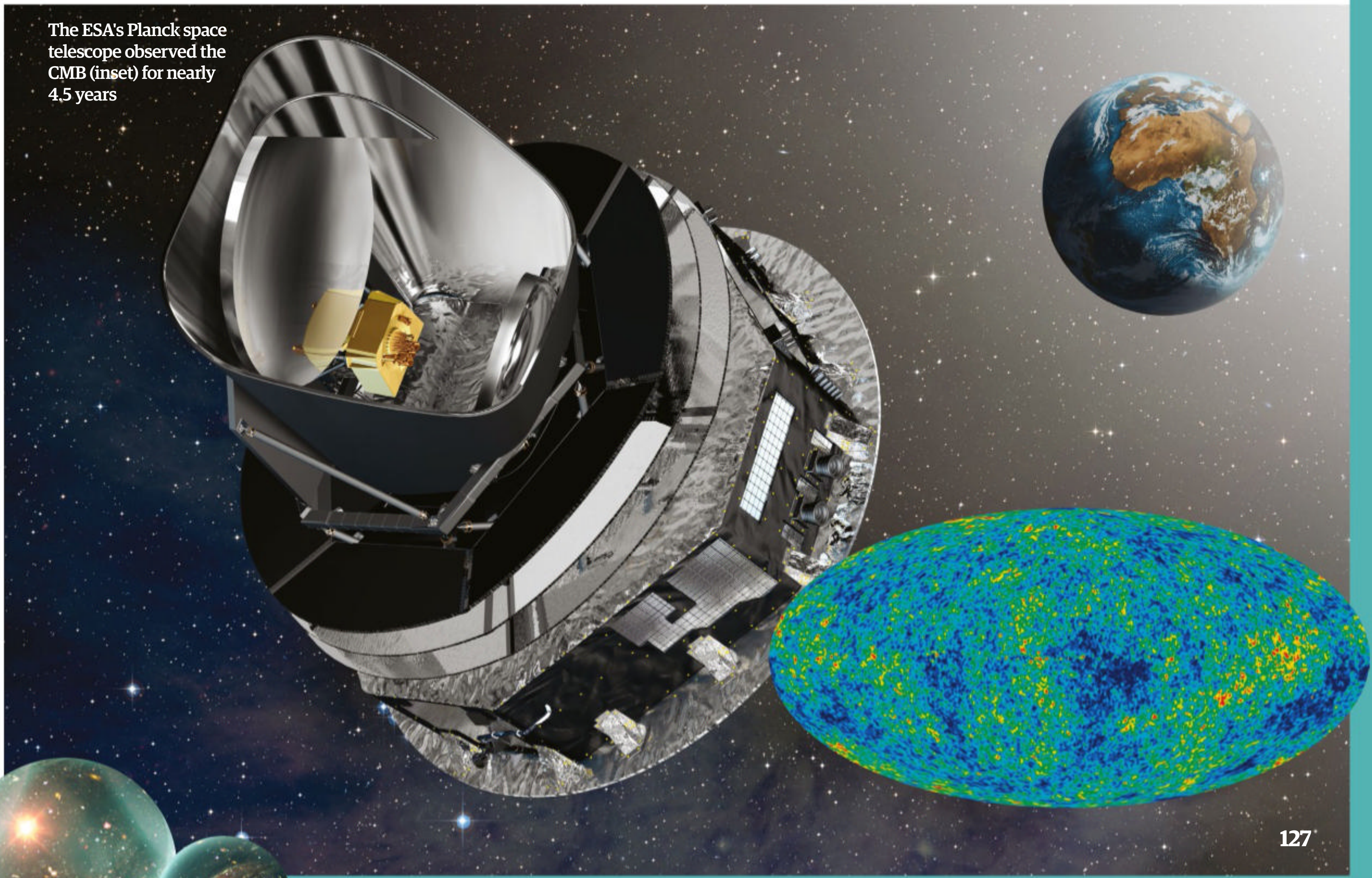
However, fellow physicist Erwin Schrödinger devised his famous Schrödinger's Cat thought experiment to show up holes in this argument. The eponymous feline is trapped in a sealed box with a hammer and a vial of poison. Whether or not the hammer falls to crack the vial depends on the outcome of a measurement on a quantum particle. The Copenhagen interpretation says that the particle is simultaneously in both states at once until the measurement is made. That means the hammer falls and doesn't fall and the cat is alive and dead until the particle is measured. But why does the act of measuring force nature to choose? Everett's alternative 'many-worlds' picture was to suggest that it doesn't – both outcomes occur. The universe splits into two distinct versions (or branches) – one where the cat lives and another where it perishes.

"If you are trying to describe the formation and evaporation of a black hole truly quantum gravitationally then you would expect multiple versions of the black hole," says Chatwin-Davies, just like there are two versions of the cat. The implications for the information paradox are profound. "If you're sitting around monitoring the Hawking radiation coming out of a black hole, you should expect to see a loss of information," he says. That's because you're limited to one of the many branches the black hole now exists in. The information about an infalling object isn't destroyed, it is simply shared out across the many branches of reality. Throw *Hamlet* into a black hole and Act I may emerge in this universe's Hawking radiation, but Act II in another.

Nomura agrees. "Focus on one world and clearly you cannot recover all the initial information," he says. What effect does this have on the firewall? "The statement that you have to go smoothly into a black hole applies only to each branch of the many worlds," says Nomura. "Whereas the rules about quantum information apply to the whole set of worlds." According to Nomura, the Firewall Paradox results from confusing these differences. Chatwin-Davies is on the same page. Comparing the two "is like comparing apples and oranges," he says.

So, as with many times in the history of physics, answering one question has thrown up several others. Information falling into a black hole may be imprinted as a hologram on the event horizon and carried back into space by Hawking radiation. It could be that severing the link between the quantum particles responsible for Hawking radiation incinerates you to a crisp as you enter, or that information could be hidden in the Hawking radiation after all. Finally, it could even be possible that information falling into a black hole is shared out among the many versions of reality that splinter off as a black hole evolves. Until we crack the elusive code of quantum gravity, it is hard to know who is right.

> "If you're monitoring the Hawking radiation from a black hole you should expect to see a loss of information" **Aidan Chatwin-Davies**



**The ESA's Planck space telescope observed the CMB (inset) for nearly 4.5 years**

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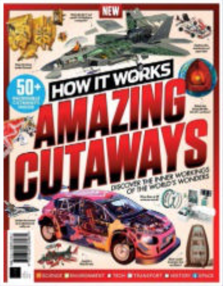
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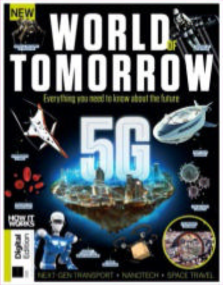
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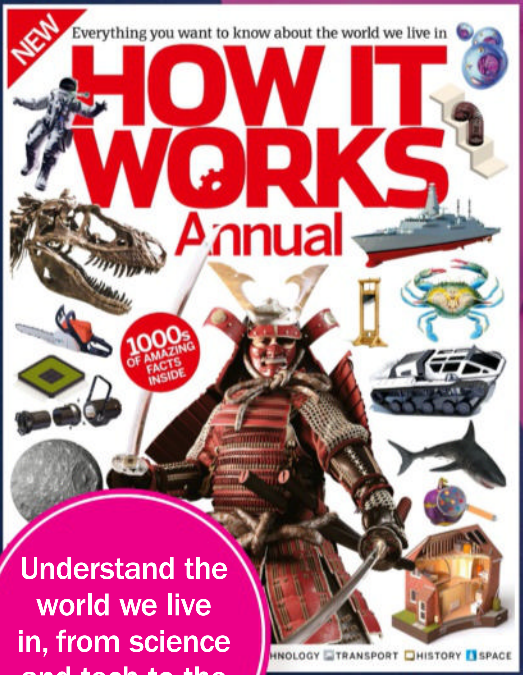
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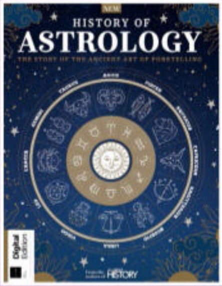
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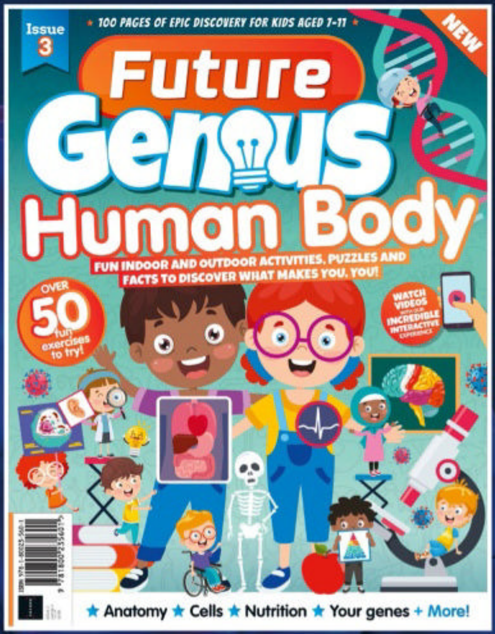
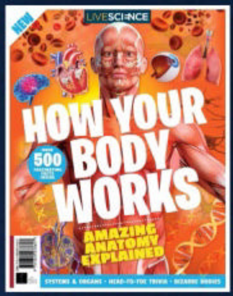

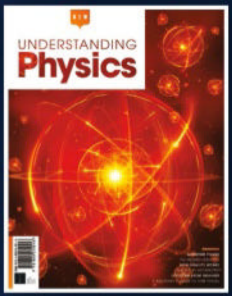

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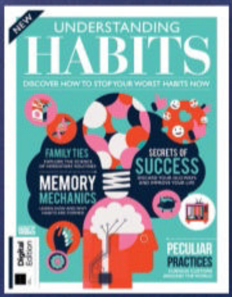
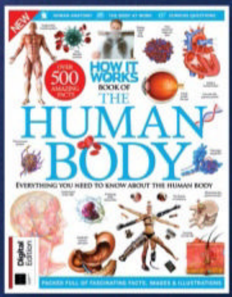

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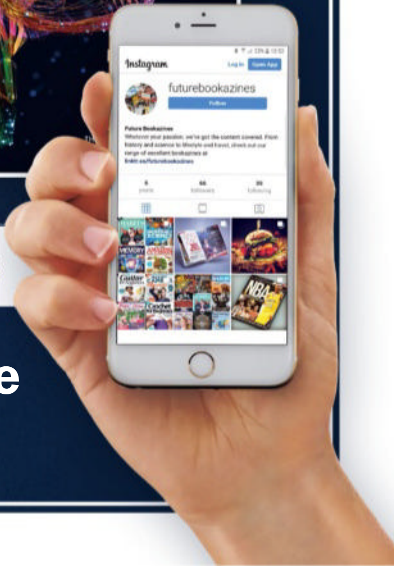

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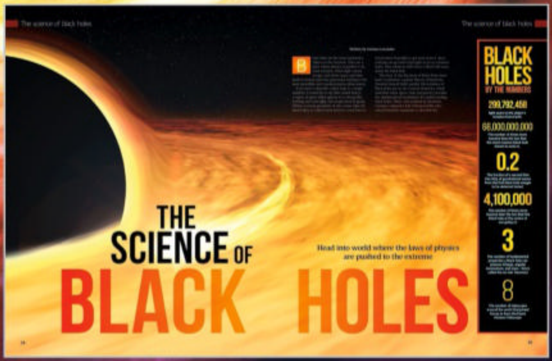

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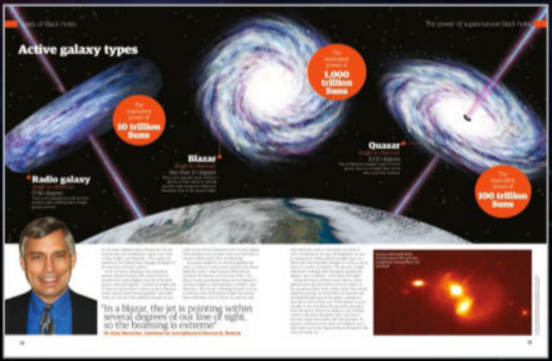

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